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THE DEVELOPMENT OF FILM BADGES CONTAINING MULTI-ELEMENT FILTERS TO REDUCE THE X-RAY ENERGY DEPENDENCE OF PHOTOGRAPHIC FILM

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THE DEVELOPMENT OF FILM BADGES CONTAINING MULTI-ELEMENT FILTERS TO REDUCE THE X-RAY ENERGY DEPENDENCE OF PHOTOGRAPHIC FILM

by

Ellery Storm
Simon Shlaer

This report expresses the opinions of the author or authors and does not necessarily reflect the opinions or views of the Los Alamos Scientific Laboratory.

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ABSTRACT

This report describes the experimental work leading to the development of flat roentgen response film badges containing multi-element filters.

The films were exposed to fluorescent x rays from 30 to 100 kev, heavily filtered direct x-ray beams from 100 to 250 kev, and isotope gamma rays from 250 to 1250 kev. Measurements showed that the unfiltered response of personnel films was 15 to 30 times greater to 40 kev x rays than to 1250 kev gamma rays. Calculations indicated that a filter consisting of several elements with K-edges evenly spaced from 40 to 90 kev could reduce the energy dependence of the film to within acceptable limits. Such multi-element filters were placed in cycolac plastic film badges. It was necessary to place copper between the multi-element filter and the film to reduce the effects of fluorescent radiation produced in the filter. Measurements made with low energy radiation showed that the film blackening behind the filter was due primarily to radiation scattering in the plastic and not to radiation passing directly through the filter. Two plastic film badges were developed with either lead frames or lead lattices placed around the filters to reduce the amount of radiation scattering into the filtered area.

The lead-frame badge contains a multi-element filter (gadolinium, erbium, tantalum, gold, and bismuth) and a 0.02 in. thick copper filter; the response of Du Pont 502, Du Pont 508, Du Pont 555, Eastman Type II, and Ilford PM-1 film in this badge is flat within 30 per cent from 40 to 1250 kev; the badge is directionally independent within 30 per cent over this energy region, but the density under the filtered area at low energies is non-uniform, the edges being darker than the central region. The lead-lattice badge contains a multi-element filter (same elements as in the frame badge, but in different proportions) and a copper filter whose thickness varies with the film type; the response of the same films listed above is flat within 30 per cent from 50 to 1250 kev; it is directionally dependent at low energies, and the density under the filtered area is uniform.

The badges were modified to permit the evaluation of thermal neutron and beta radiation; these modifications did not affect the photon film response of the lattice badge, but the frame badge was now directionally dependent by as much as a factor of 3 because of the reduced size of the filters. A method of measuring thermal neutrons was devised using two multi-element filters having similar photon responses; one filter containing gadolinium gave a Co^{60} gamma ray to thermal neutron exposure ratio of 1.43 r/rem, and a second filter containing molybdenum instead of gadolinium gave a ratio of 0.70 rem. The film badge response on a phantom was higher than in air by a factor of 1.56. An estimate was made of the accuracy of the gamma exposure evaluation when the film is exposed to both gamma and fast neutron radiation; film badges exposed to the Godiva critical assembly read 70 per cent higher than glass dosimeter rods exposed at the same time and in the same location.

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INTRODUCTION

The purpose of this report is to describe the experimental work performed at Los Alamos which sought to reduce the x-ray energy dependence of a photographic film by means of a filter composed of several elements. The response in roentgens of a photographic film is nearly constant from above 1000 kev down to 200 kev, but rises rapidly below 200 kev and reaches a peak at 40 kev. The response of a film to 40 kev x rays is 15 to 30 times greater than to 1000 kev x rays.

For the past several years Group H-1 of the Health Division of the Los Alamos Scientific Laboratory has been in the process of designing a new film badge for measuring personnel exposure to x and gamma rays, beta rays, and neutrons. As a part of this project a design for a filter for the new badge which could be used with Du Pont 502 personnel monitoring film was requested. The filter was to reduce the photon energy dependence of the film to as small a value as practicable and over as wide an energy range as possible. Our work showed that it is possible to hold the film response to within 30 per cent over the energy range from 40 to above 1000 kev. This report describes the multi-element filters which were designed to meet these requirements.

The report begins with a brief review of previous attempts to deal with the energy dependence problem and explains why a single filter containing several elements was chosen. Next, the method of calculating the amount of material required in the filter and the energy dependence reduction produced by the filter is described. The experimental work that followed is presented in the order in which it was performed.

First the calculated and measured filtered film responses were compared and found not in agreement, presumably because of fluorescent radiation produced in the filter. A satisfactory film response was obtained when copper was placed between the multi-element filter and the film to reduce the effects of the fluorescent radiation. Directional dependence and other measurements with the multi-element filters in plastic badges revealed that the film blackening behind the filter was due primarily to radiation scattering in the plastic, not to radiation passing directly through the filter. Two plastic film badges were developed containing either lead frames or lead lattices around the filters to reduce the amount of radiation scattering into the filtered area. The photon response of Du Pont 555 and 508, Eastman Type II, and Ilford PM-1 films in these badges was measured both in air and on a phantom. Finally, the thermal and fast neutron response of these badges was measured and a method of measuring personnel exposure to thermal neutrons was devised.

The Appendix contains a description of the three types of photon sources employed to measure the energy response of the film, followed by the measurements of the beam uniformity, spectrum purity, and exposure rates of each type of source.

PHOTON ENERGY DEPENDENCE OF FILM

The response to photons of unfiltered Du Pont 502 personnel monitoring film is shown in Fig. 1. The relative sensitivity of the film, defined as the reciprocal roentgen exposure required to obtain a constant film density, is shown versus the energy of the x rays on a log-log plot; the reciprocal roentgen exposure has been set equal to 1 at 1250 kev. The figure shows that to obtain a constant density, about 25 times more exposure is required with 1250 kev than with 40 kev x rays. Since the x-ray energy of personnel exposure is generally unknown, it is apparent that the energy dependence of the film is perhaps the largest source of error in trying to measure personnel exposure with film badges.

Methods of Dealing with the Energy Dependence Problem

Basically, three methods have been used to deal with the energy dependence problem.

One method is to calibrate the film directly to the sources being used by personnel. At Los Alamos there are too many different kinds

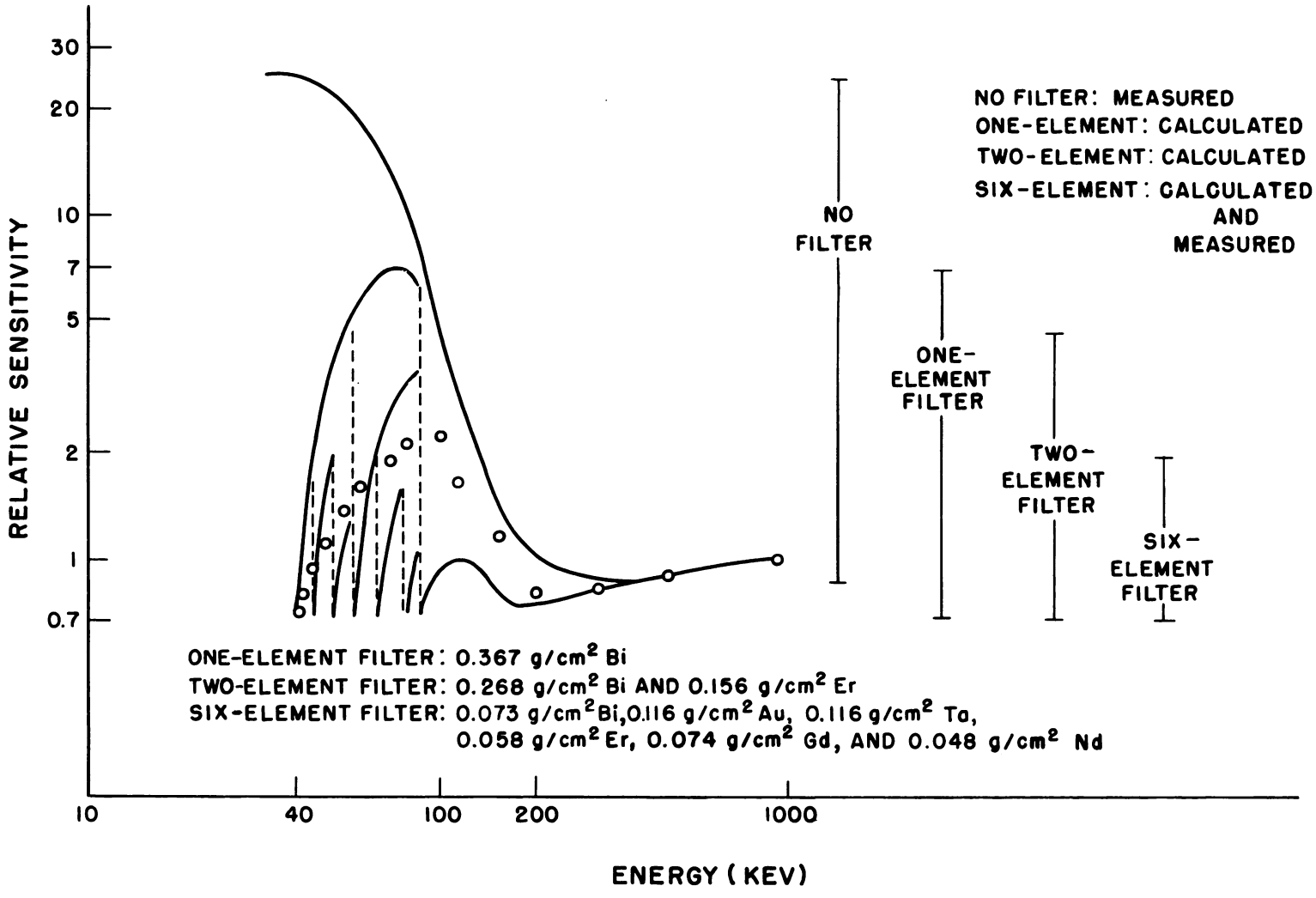

Fig. 1. The photon response of Du Pont 502 film unfiltered and filtered by one-element, two-element, and six-element filters.

of sources and exposure conditions to permit the use of this method on a routine basis.

A second method is to determine the energy of the x rays by means of two or more different filters on the film. The filters differ in atomic number or thickness, resulting in different densities under each filter when the film is exposed to low energy x rays. The ratio of the exposures corresponding to the different densities under the different filters is assumed to be unique with energy and is used to determine the x-ray energy and therefore the exposure. This method has been employed at Los Alamos for the last ten years,[1] and experience has shown that it is subject to several sources of error. One is that the exposure ratio is not unique with energy. For example, the exposure ratio obtained with a monochromatic source at 40 kev may differ by more than a factor of 2 from that obtained with a continuous-spectrum source having an effective energy of 40 kev. The degree to which the exposure ratios obtained with monochromatic and continuous-spectrum sources differ depends on the peak energy and filtration of the continuous-spectrum source. Another source of error is exposure of the films to two or more photon energies, because the exposure ratios are affected by the proportion of each energy given the film. This is illustrated in Table I, which shows the results of trying to evaluate by exposure ratios films exposed to different proportions of 66 and 1250 kev radiation. The interpreted exposures differ from the true exposures by as much as a factor of 3.

TABLE I

INTERPRETATION OF FILMS EXPOSED TO TWO X-RAY ENERGIES USING EXPOSURE RATIOS OBSERVED UNDER TWO FILTERS

Film Number	66 kev Exposure (r)	1250 kev Exposure (r)	Total True Exposure (r)	Interpreted Exposure (r)	Ratio of True to Interpreted Exposure
1	0.1	0.1	0.2	0.12	0.60
2	0.1	0.4	0.5	0.54	1.08
3	0.1	1.5	1.6	1.3	0.81
4	0.4	0.1	0.5	0.19	0.38
5	0.4	0.4	0.8	0.48	0.60
6	0.4	1.5	1.9	1.4	0.74
7	1.5	0.1	1.6	0.49	0.31
8	1.5	0.4	1.9	0.74	0.39
9	1.5	1.5	3.0	1.4	0.47

A third method of dealing with the energy dependence problem is to use some means of reducing the energy dependence of the film. This was the method chosen for the new Los Alamos film badge. Although several ingenious methods have been devised to reduce the energy dependence of a film,[2,3,4] none of them appeared to be adaptable to the new badge. The new Los Alamos badge was to have a single filter capable of reducing the photon energy dependence so that the response would not exceed the limits of 0.7 to 1.3 from about 40 to 1250 kev. In addition, the badge was to have a second filter with a similar x-ray response which would also provide a measure of personnel exposure to thermal neutrons.

After preliminary film response measurements and calculations were performed to determine how the response was affected by filters of different atomic number and thickness, it appeared that a single filter containing several elements could be designed to meet the requirements of the new Los Alamos badge.

Energy Dependence Reduction by a Multi-Element Filter

Calculations were first performed to determine how much a one-element filter would reduce the measured unfiltered Du Pont 502 film response. In the calculations only the direct absorption in the filter was considered and the true absorption coefficients[5] derived from NBS Circular 583[6] were employed. An element with a K-edge near

90 kev was selected and its thickness was chosen so that a relative sensitivity of 0.7 would be obtained for the low value at the K-edge. The calculated film response obtained with the one-element filter is shown in Fig. 1. Above 90 kev the sensitivity lies within 0.7 to 1.1. Below 90 kev the curve peaks at a sensitivity of about 7. When a second element having a K-edge at 58 kev is added and the thickness of the two-element filter is adjusted so that a sensitivity of 0.7 is obtained for both low K-edge values, the sensitivity is unchanged above 90 kev, but below 90 kev a double peaked curve is obtained, and the sensitivity of the peak does not exceed 5. The calculated response of the two-element filter is shown in Fig. 1.

The trend is now evident; as more and more elements with K-edges between 40 and 90 kev are added to the filter, the sensitivity above 90 kev remains unchanged, but the sensitivity below 90 kev steadily decreases. Figure 1 shows that a film response lying within 0.7 to 2.0 is obtained over an energy range of 40 to above 1000 kev with a filter consisting of six elements whose K-edges are about evenly spaced between 40 and 90 kev. If a filter containing all the elements with K-edges between 40 and 90 kev were used over the film, the calculated response would lie between the desired limits of 0.7 to 1.3.

Calculation of the Energy Dependence Reduction

The amount of material required in the filter was calculated as follows. First assume that the unfiltered film response is to be reduced using only one element. Since there are two values of the absorption coefficient at the K-edge energy of the element, there will be two response values, the larger one corresponding to the lower value of the true absorption coefficient and the smaller to the higher value. The smaller response value at the K-edge is not to go below a defined limit, F_k; and the thickness, x, which reduces the response to that limit will be used in the filter. If F_o is the unfiltered film response at the K-edge energy, then F_k is given by

$$F_k = F_o e^{-\mu_h X} \quad , \text{ or}$$

$$\mu_h x = \ln F_o - \ln F_k$$

where μ_h is the higher K-edge value of the true absorption coefficient. The response of the film, F_f, filtered by the element of thickness x, is calculated as a function of energy using the equation

$$F_f(E) = F_o(E) e^{-\mu(E)x} \quad ,$$

where $F_o(E)$ is the unfiltered film response at energy E, and $\mu(E)$ is the true absorption coefficient of the element at each energy E.

Now assume that the response is to be reduced using two elements. Each element has a K-edge, and the smaller response value at each edge is not to go below the defined limit F_k. Let F_{o_1} and F_{o_2} be the

unfiltered film responses at the K-edge energy of element 1 and 2, respectively. Then the thickness, x_1, of element 1 and the thickness, x_2, of element 2 which gives F_k are obtained by solving the following set of equations:

$$\mu_{h_1} x_1 + \mu_2 x_2 = \ln F_{o_1} - \ln F_k$$

$$\mu_1 x_1 + \mu_{h_2} x_2 = \ln F_{o_2} - \ln F_k \quad ,$$

where μ_{h_1} is the higher K-edge value of the true absorption coefficient of element 1 at the K-edge energy of element 1, μ_2 is the true absorption coefficient of element 2 at the K-edge energy of element 1, μ_1 is the true absorption coefficient of element 1 at the K-edge energy of element 2, and μ_{h_2} is the higher K-edge value of the true absorption coefficient of element 2 at the K-edge energy of element 2. The response of the film, F_f, filtered by thickness x_1 of element 1 and thickness x_2 of element 2, is calculated as a function of energy using the equation

$$F_f(E) = F_o(E) e^{-[\mu_1(E)x_1 + \mu_2(E)x_2]} \quad ,$$

where $F_o(E)$ is the unfiltered film response at energy E, $\mu_1(E)$ is the true absorption coefficient of element 1 at energy E, and $\mu_2(E)$ is the true absorption coefficient of element 2 at energy E.

Similarly, for a filter containing n elements, the element thicknesses which reduce the smaller film response values at the K-edges to F_k are obtained by solving the following n equations:

$$\mu_{h_1} x_1 + \mu_2 x_2 + \mu_3 x_3 + \cdots + \mu_n x_n = \ln F_{o_1} - \ln F_k$$

$$\mu_1 x_1 + \mu_{h_2} x_2 + \mu_3 x_3 + \cdots + \mu_n x_n = \ln F_{o_2} - \ln F_k$$

$$\mu_1 x_1 + \mu_2 x_2 + \mu_{h_3} x_3 + \cdots + \mu_n x_n = \ln F_{o_3} - \ln F_k$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

$$\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \cdots + \mu_{h_n} x_n = \ln F_{o_n} - \ln F_k$$

The response of the film, F_f, filtered by the n elements is calculated as a function of energy using the equation

$$F_f(E) = F_o(E) e^{-[\mu_1(E)x_1 + \mu_2(E)x_2 + \mu_3(E)x_3 + \cdots + \mu_n(E)x_n]}$$

Comparison of Calculated and Measured Filtered Film Response

To test the theory of the multi-element filter, a six-element filter was constructed and a comparison was made of its calculated and measured film response.

The elements in the filter were chosen primarily on the basis of the location of their K-edges, although other factors served to restrict the selection. For example, all elements above an atomic number of 83 are naturally radioactive and would fog the film; thus the K-edge of bismuth, located at 90 kev, was the highest that could be used. Since the calculations indicated that the film response is improved when the K-edges of the elements are separated by equal energy intervals, an attempt was made to select elements whose K-edges are separated by 10

kev intervals. However, availability and the chemical stability of the elements limited the selection. The six elements finally chosen for the filter and the location of their K-edges are given in Table II, together with the amount of each element placed in the filter.

The filter was constructed by powder metallurgy techniques and placed in a plastic badge containing the film. One filter was placed on each side of the film. The filters were 1/2 x 1 in. in size.

As shown in Fig. 1, the measurements do not agree with calculation. There is no evidence of any K-edge structure, and a continuous curve can be drawn through the measured points. In addition, the points show an oversensitivity of 2.3 in the film response at about 100 kev.

One cause for the disagreement between measurement and calculation is the fluorescent radiation produced in the filter by the primary photon radiation. In the calculations, absorption coefficients for monochromatic sources are employed and it is assumed that the monochromatic radiation incident on the filter is merely attenuated and not changed in spectrum in passing through the filter. In reality the spectrum is changed or degraded by Compton scatter and especially by fluorescent radiation produced in the filter. The absorption coefficient corresponding to the energy spectrum emerging from the filter and incident on the film lies between the upper and lower

TABLE II

THE SIX-ELEMENT FILM FILTER

Elements	Atomic Number	Amount of Element (g/cm^2)	Form of Element	K-edge Energy (kev)
Neodymium	60	0.048	Nd_2O_3	43.571
Gadolinium	64	0.074	Gd_2O_3	50.229
Erbium	68	0.058	Er_2O_3	57.483
Tantalum	73	0.116	Ta powder	67.400
Gold	79	0.116	Au powder	80.713
Bismuth	83	0.073	Bi powder	90.521

K-edge values; consequently, the film response is smeared, and the K-edge discontinuities cannot be resolved. The oversensitivity occurs at 100 kev where the energy is high enough to excite the fluorescent x rays of all the elements in the filter.

The amount of fluorescent radiation produced in the filter can be minimized by the proper selection and placement of the elements in the filter. For example, assume the filter can be constructed in layers of elements arranged in descending order of atomic number with the element of largest atomic number farthest from the film. The K_{α_1} line of each element would be absorbed by the element beneath it whose K-edge energy would be just below the K_{α_1} energy; hence, only the fluorescent radiation from the lowest atomic number element would reach the film. This scheme was not adopted because the filter could not be constructed easily in layers. The Powder Metallurgy Group (CMB-6) at Los Alamos fabricated the filter and found it was much simpler to mix the elements uniformly.

By placing a low atomic number filter, such as copper, between the six-element filter and the film, the amount of fluorescent radiation reaching the film can be greatly reduced. In addition, the 8 kev fluorescent x ray produced in the copper does not significantly affect the film response. On the basis of fluorescent reduction measurements made by Ehrlich,[7] a 0.02 in. thick copper filter was placed between the film and the six-element filter to reduce the fluorescent radiation.

Measurements of the film response were made with the 0.02 in. thick copper filter between the film and the six-element filter. Although the sensitivity at 100 kev was indeed reduced to 1, the film response cut off sharply below this energy. Consequently, a new filter was designed.

Film Response of Multi-Element Filter plus Fluorescent Absorber

The film response under the 0.02 in. thick copper filter was calculated. The measured unfiltered film response of Du Pont 502 is shown again in Fig. 2, where the relative sensitivity is plotted versus the photon energy; the relative sensitivity has been set equal to 1 at 1250 kev. Also shown in Fig. 2 are both the calculated and measured film response under the copper filter. The small discrepancy between the calculated and measured copper-filtered film response is probably due to the 8 kev copper fluorescent radiation which was not included in the calculation. Below 100 kev the copper significantly reduces the response; for example, the unfiltered curve peaks at 40 kev with a sensitivity of 25, whereas the copper-filtered curve peaks at 65 kev with a sensitivity of about 12.

Calculations were next performed to determine the amount of material required in the six-element filter to reduce the energy dependence of the copper-filtered film to within acceptable limits. The same elements listed in Table II were employed in this calculation, and, again, the sensitivity for the lower K-edge values was not

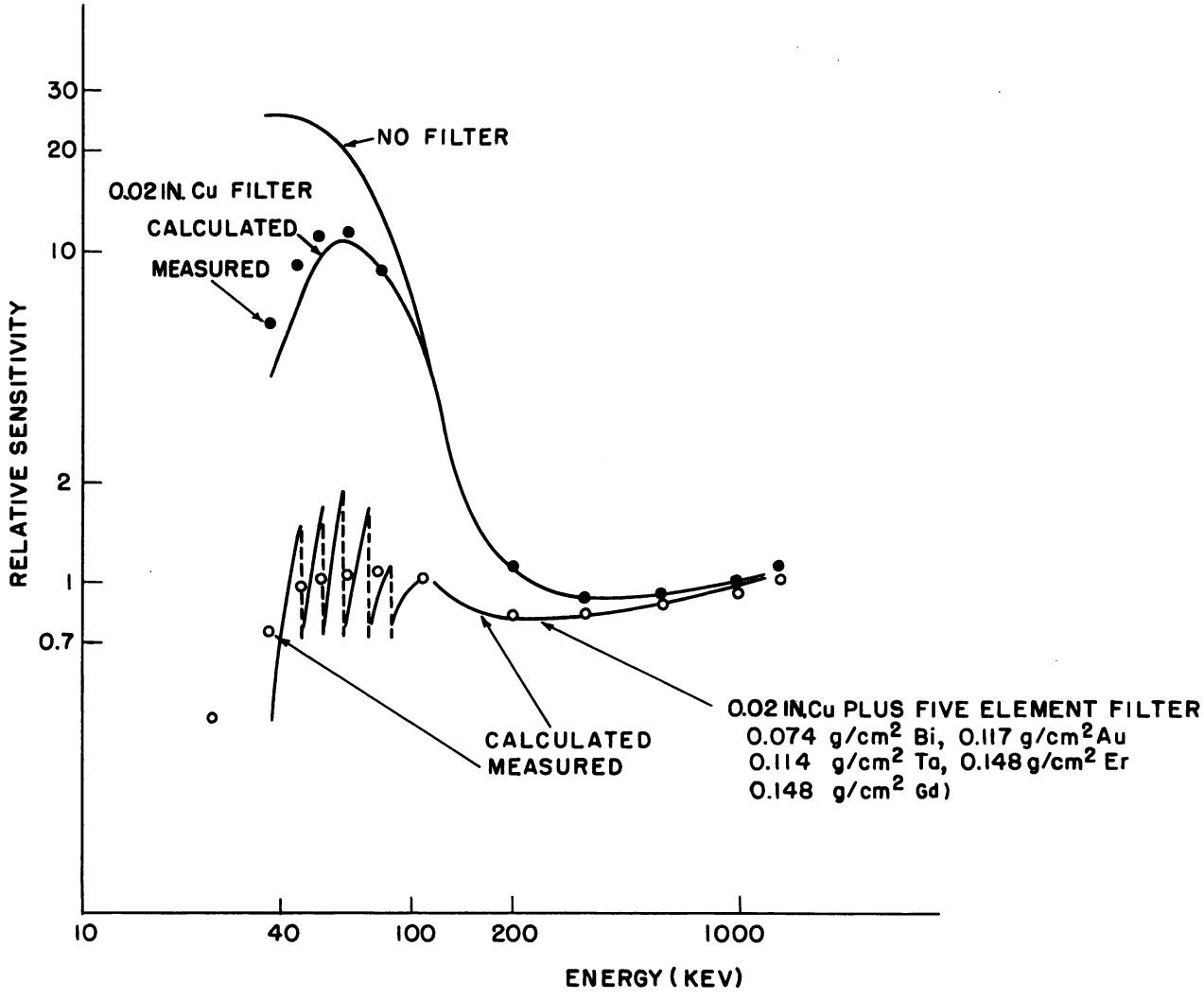

Fig. 2. The photon response of Du Pont 502 film unfiltered and filtered by 0.02 in. copper and by 0.02 in. copper plus a five-element filter.

permitted to go below 0.7. With the copper added to the filter, the lowest atomic number element, neodymium, was dropped from the six-element filter to prevent the response from falling off too rapidly at the lower energies. Figure 2 shows the calculated film response obtained with the copper plus five-element filter; the calculated response lies within a sensitivity of 0.7 to 1.8 from about 40 to 1250 kev. The five elements, the amount of each element, and the location of their K-edges are listed in Table III.

Film response measurements with the copper plus five-element filter were then made and compared to the calculations. Filters 1/2 x 1 in. in size were constructed by powder metallurgy techniques and placed in a cycolac plastic badge containing the film. The copper plus five-element filters were placed on each side of the film; the 0.02 in. thick copper filters were between the film and the five-element filters.

As shown in Fig. 2, the measurements do not agree with calculation below 100 kev. There is no indication of any K-edge structure, and a continuous curve can be drawn through the measured points. The discrepancy between measurement and calculation again appeared to be caused by the secondary radiation produced in the filter by the primary photon radiation and by scatter. Since the copper filter merely reduces the fluorescent radiation reaching the film and does not entirely absorb it, the spectrum emerging from the filter and incident on the

TABLE III

THE FIVE-ELEMENT FILM FILTER

Elements	Atomic Number	Amount of Element (g/cm^2)	Form of Element	K-edge Energy (kev)
Gadolinium	64	0.148	Gd_2O_3	50.229
Erbium	68	0.148	Er_2O_3	57.483
Tantalum	73	0.114	Ta powder	67.400
Gold	79	0.117	Au powder	80.713
Bismuth	83	0.074	Bi powder	90.521

Total amount of material including a 3% paraffin binder = 0.619 g/cm^2.

film is still smeared and prevents the K-edge discontinuities from being resolved. Between 40 to 90 kev the measured points lie about midway between the peaks and valleys of the calculated K-edge structure. The copper did absorb enough of the fluorescent radiation to decrease the oversensitivity at 100 kev to about 1.2. All the measured points lie between a sensitivity of 0.7 to 1.2 from 40 to 1250 kev.

The original problem of obtaining a multi-element filter which would reduce the energy dependence of the film so that the response would not exceed the limits of 0.7 to 1.3 from about 40 to 1250 kev appeared to be solved. The film would be calibrated to the 1250 kev Co^{60} source, and all personnel films exposed to either monochromatic or continuous-spectrum photon radiation would be evaluated from this one calibration curve; the accuracy of the evaluation would be 30 per cent, provided the photon energy fell within the energy region of 40 to 1250 kev. Below 40 kev the filter cuts off the film response, and the photon exposure would not be recorded; above 1250 kev the film response gradually increases, reaching a sensitivity of about 1.6 at 10 Mev.[8]

FLAT X-RAY RESPONSE FILM BADGES

The thickness of plastic necessary to obtain electron equilibrium with the Co^{60} source was then determined. The electron equilibrium plastic employed was Acrylonitrile Butadiene Styrene which is referred to in this report as "cycolac" plastic. When film response measurements were made at lower photon energies with the 0.04 in. thickness of electron equilibrium cycolac plastic between the film and the copper plus multi-element filter, unexpected results were obtained which led to the re-design of the new film badge and the development of the relatively flat response "frame" and "lattice" type badges described in the following sections.

The Effect of Badge Scatter on the Filtered Film Response

Calculations indicated that the 0.04 in. electron equilibrium thickness of plastic between the copper and film wrapper would not affect the film response in the low energy x-ray region. For example, the plastic would be expected to reduce the response by about 6 per cent at 40 kev. However, measurements showed that the film response was significantly affected by the plastic.

Figure 3 shows again the measured response of the Du Pont 502 film filtered by the copper plus five-element filter described in Table III. The response lies within a sensitivity of 0.7 to 1.2 from about 40 to 1250 kev. Figure 3 also shows the measured response of the Du Pont 502 film filtered by the same copper and five-element filter plus 0.04 in. thick plastic between the film wrapper and copper. Instead of producing a small decrease in the film response, the plastic increased the film response below 100 kev, raising the peak sensitivity from 1.2 to 1.4.

The thickness of plastic between the copper and film wrapper was increased from 0.04 in. to 0.1 in. to see what would happen. As Fig. 3 shows, the film response in the low energy region increased still further, and the peak sensitivity rose from 1.4 to 1.7.

The filters employed in these measurements were 1/2 x 1 in. big, and they were contained in a plastic badge. The new Los Alamos film badge was being designed about this time by Group H-1 and it was found necessary to decrease the size of the filter. The new badge was to be made of the cycolac plastic and was to contain three filter areas of which two were to contain the photon-energy independent filters with very little filtration, and one was to be used to evaluate β-rays and photons below 50 kev. Because of the requirement of these areas, the filter size could not be much larger than 1 x 1 cm. Consequently, multi-element filters 1 x 1 cm in size were constructed and their film response measured.

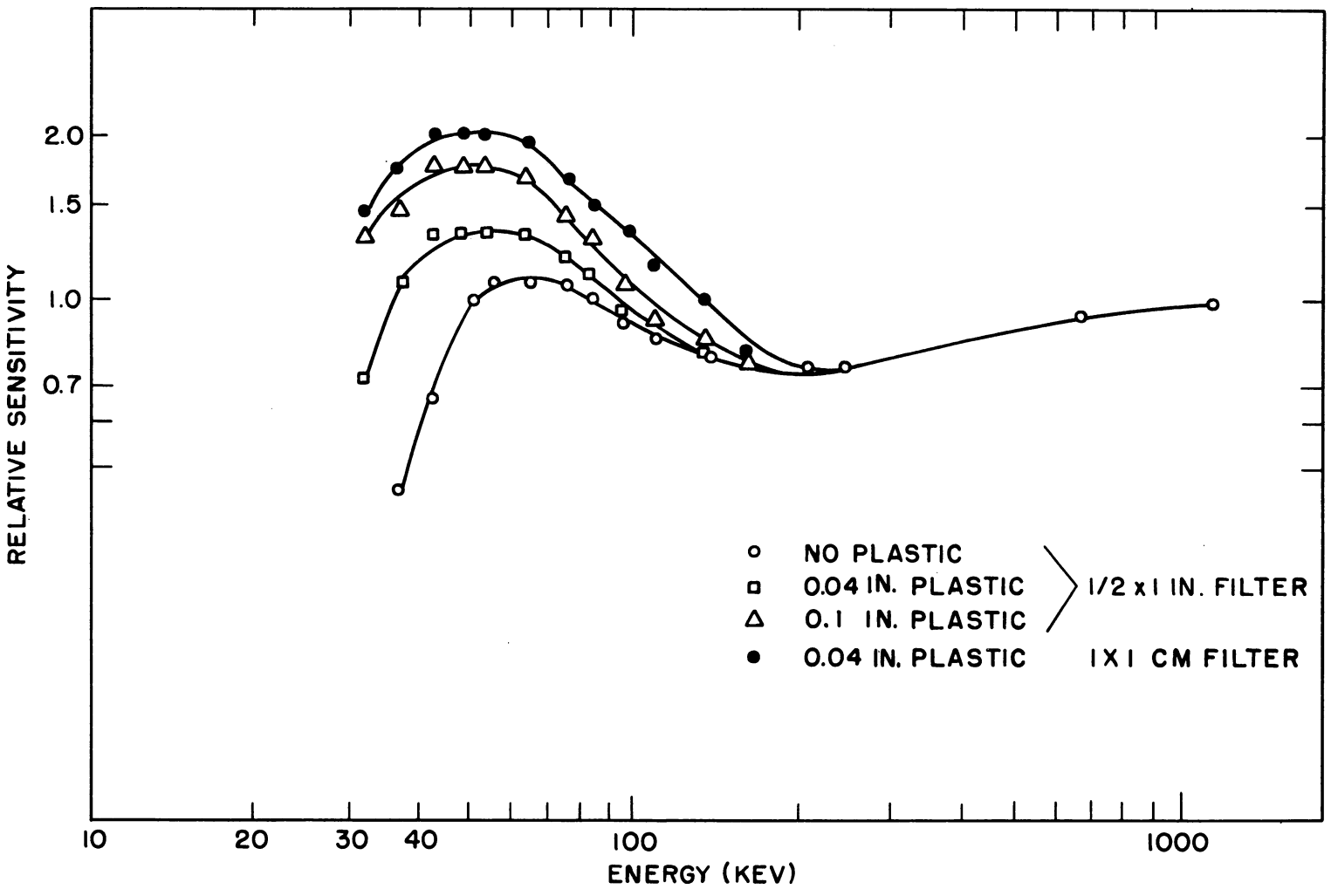

Fig. 3. The x-ray response of Du Pont 502 film filtered by copper plus a five-element filter; effect on film response of adding plastic between filter and film and of changing filter size.

The Du Pont 502 film response filtered by the 0.04 in. plastic plus copper plus the five-element filter in the 1/2 x 1 in. size had reached a peak sensitivity of 1.4 in the low energy x-ray region. As Fig. 3 shows, these same filters in the 1 x 1 cm size gave a much larger film response to low energy x rays, reaching a peak sensitivity of 2.0. Thus the film response was varying not only with the thickness of plastic between the film and filters but also with the size of the filters.

An examination of the films revealed that the density under the filtered area of those films exposed to radiation below 100 kev was non-uniform. The filtered area was darker at the edges than at the center. In the film response measurements given in Fig. 3 the densities were measured with an Eberline densitometer which reads an 0.6 x 0.6 cm area. Density measurements with an Ansco densitometer, which reads a 0.25 cm circular area, gave essentially the same film response when the densities were read in the center of the filtered area.

The directional dependence of the film badge containing the 0.04 in. plastic plus copper plus five-element filter was now calculated and measured in the expectation that the results might help to explain the unusual effects that had been observed. The calculated directional dependence is shown in Fig. 4, where the relative response of the Du Pont 502 film to 66 kev x rays is plotted versus the angle of the radiation in degrees. When the x rays are normal to the film, the angle of

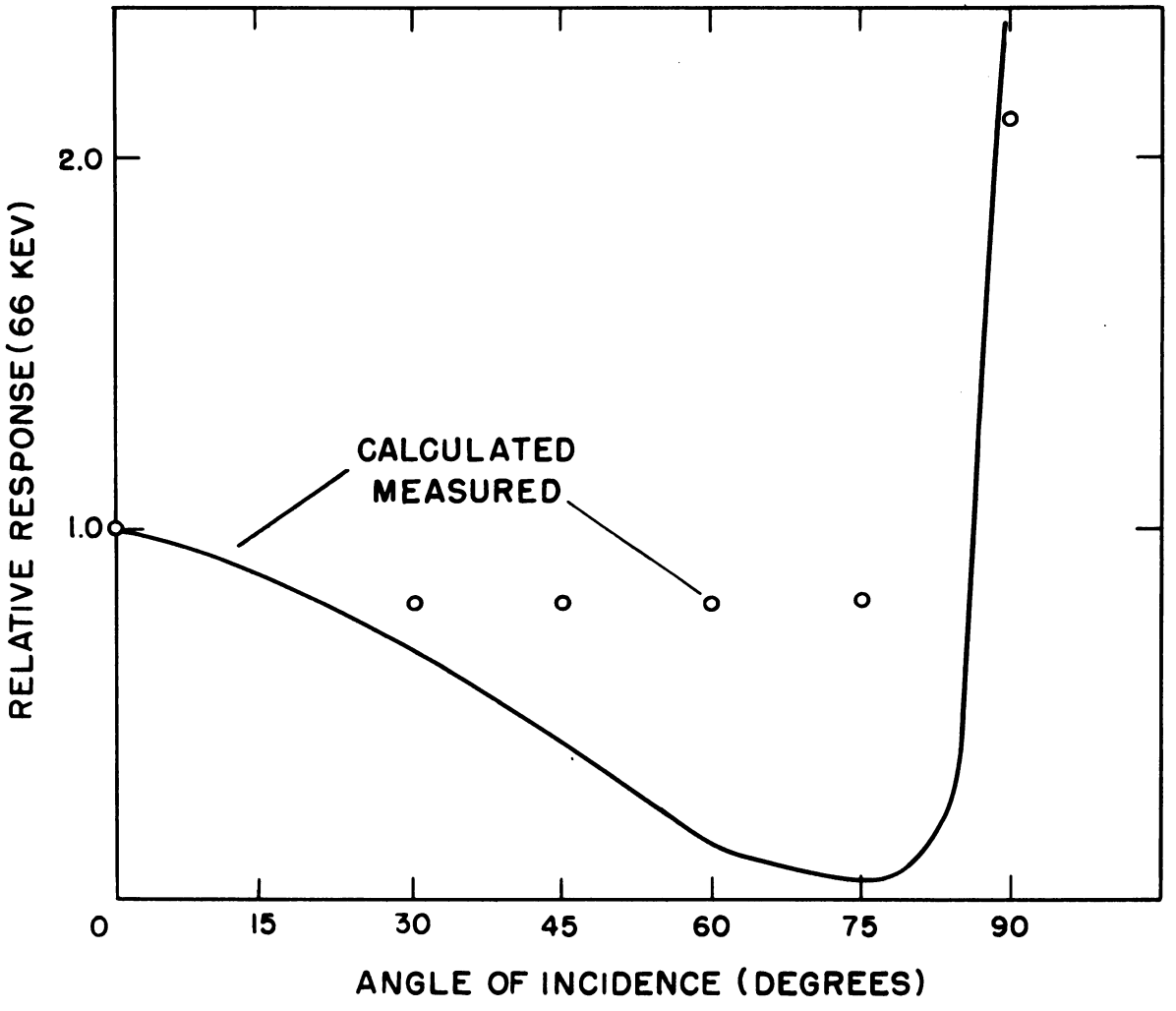

Fig. 4. Calculated and measured directional dependence of Du Pont 502 film filtered by 0.02 in. plastic plus copper plus five-element filter in plastic badge.

incidence is taken as zero degrees; when the x rays are parallel to the edge of the film, the angle is 90 degrees. The directional dependence was calculated assuming the effective thickness traversed by the radiation at an angle of incidence θ was given by $t/\cos\theta$, where t is the thickness of the filter at zero degrees.

Figure 4 shows that as the angle of incidence increases the calculated film response falls off rather sharply, reaching a minimum at about 75 degrees. When the angle approaches 90 degrees, where there is no filter between the source and the film, the response increases rapidly because of the over-sensitivity of the unfiltered film to low energy x rays. As shown in Fig. 4, the measured directional dependence of the badge did not agree with calculation. The measured film response is relatively flat and down to a relative response of only 0.8 at 75 degrees. The measured response can be made directionally independent within 30 per cent from 0 to 90 degrees by lining the edge of the badge with 0.02 in. of lead.

In these measurements with the film in a plastic badge and filtered by the plastic plus copper plus five-element filter, there were now four effects which had been observed. First, the film response was varying with the thickness of plastic between the film wrapper and copper. Second, the film response was varying with the size of the filter. Third, when the films were exposed to radiation below 100 kev in energy,

the density under the filtered area was non-uniform. Fourth, the film badge was not as directionally dependent as calculation had indicated. One way of explaining these effects was to assume that a portion of the blackening observed under the filtered area was not produced by radiation passing directly through the filter, but instead by radiation scattering in the surrounding plastic and entering into the filtered area.

If blackening in the filtered area was caused by scatter in the surrounding plastic, then adding more plastic both around and under the filter would increase the scatter and blackening. The blackening due to scatter would vary inversely with the size of the filter, increasing as the filter size was decreased. Low energy radiation scattering in the surrounding plastic would produce non-uniform blackening in the filtered area with the edges of the filter darker than the central region. Finally, directional dependence is caused by an effectively thicker filter between the radiation and film as the angle of incidence is increased; but if the blackening under the filter is not caused primarily by radiation passing directly through the filter, then the blackening would be relatively insensitive to the direction of the radiation.

To test this theory, film response measurements were made with the plastic plus copper plus five-element filters in lead badges, one of which is shown in Fig. 5a. The lead badges were made sufficiently

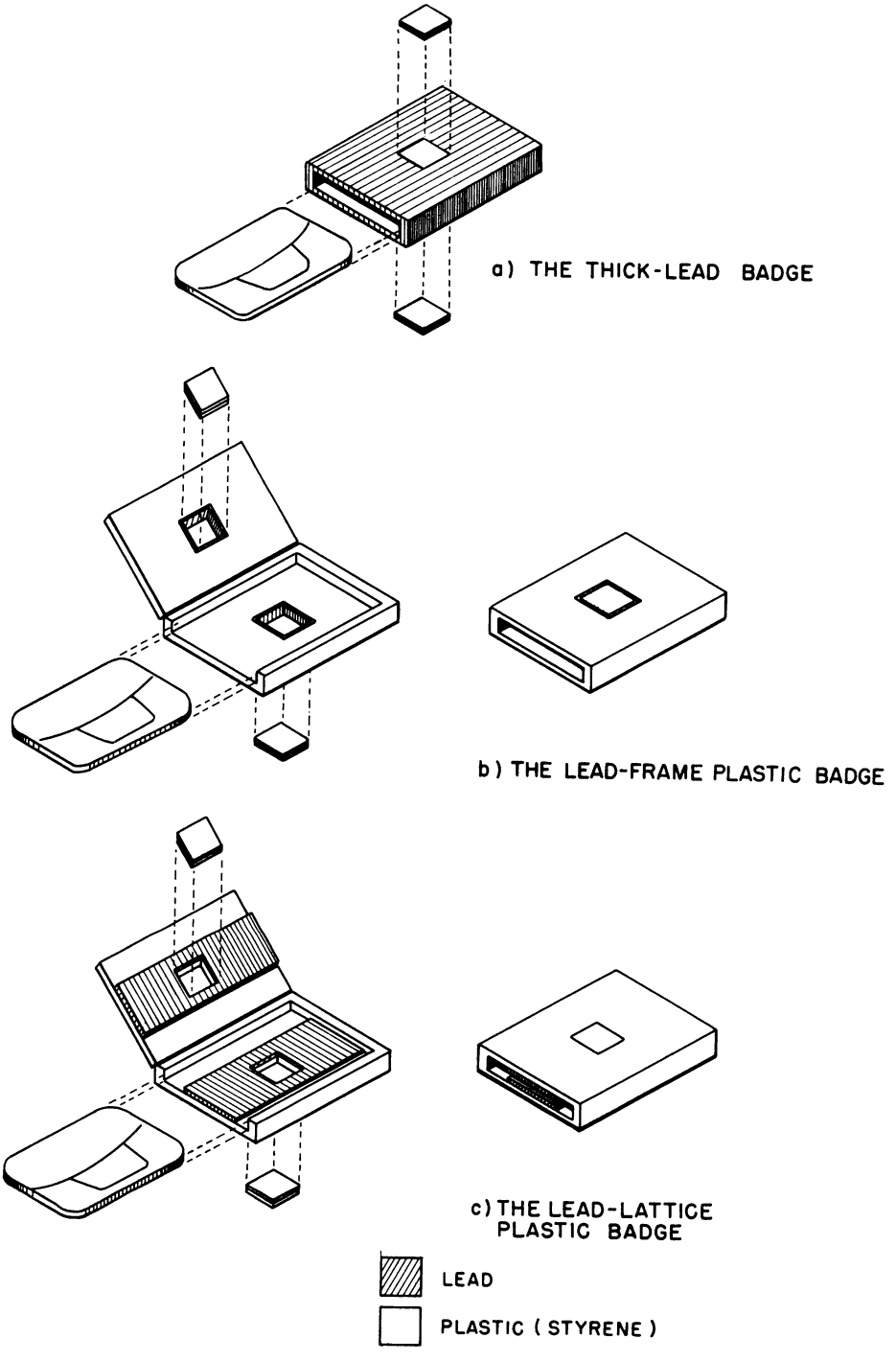

Fig. 5. Drawing showing: (a) thick-lead badge, (b) lead-frame plastic badge, and (c) lead-lattice plastic badge.

thick so that blackening could be produced only by radiation passing directly through the filter. At each energy the density surrounding the filter was measured and found to be no greater than the density of an unexposed control film, verifying that only radiation passing directly through the filter was being recorded under the filtered area.

The Du Pont 502 filtered film response in the lead badge was much different from its response in the plastic badge. In the lead badge the film response did not vary with the plastic thickness between the copper and film wrapper; within 10 per cent, the same film response was obtained with no plastic and with 0.1 in. of plastic between the copper and film wrapper. In the lead badge the film response did not vary with the size of the filter; within 5 per cent, the same film response was obtained with the 1/2 x 1 in. and the 1 x 1 cm filters. In addition, the density under the filtered area was uniform, and the directional dependence of the filter now agreed with calculation. These measurements in the lead badge confirmed the theory that the unusual effects observed with the plastic badge were due to radiation scattering in the plastic surrounding the filter and producing blackening in the filtered area.

The magnitude of the scattering effect at 66 kev is shown in Fig. 6. The measured response of Du Pont 502 film filtered by the 1 x 1 cm copper plus five-element filter in the thick-lead badge has been set equal to 1.0. When the same filter is placed on the film wrapper with

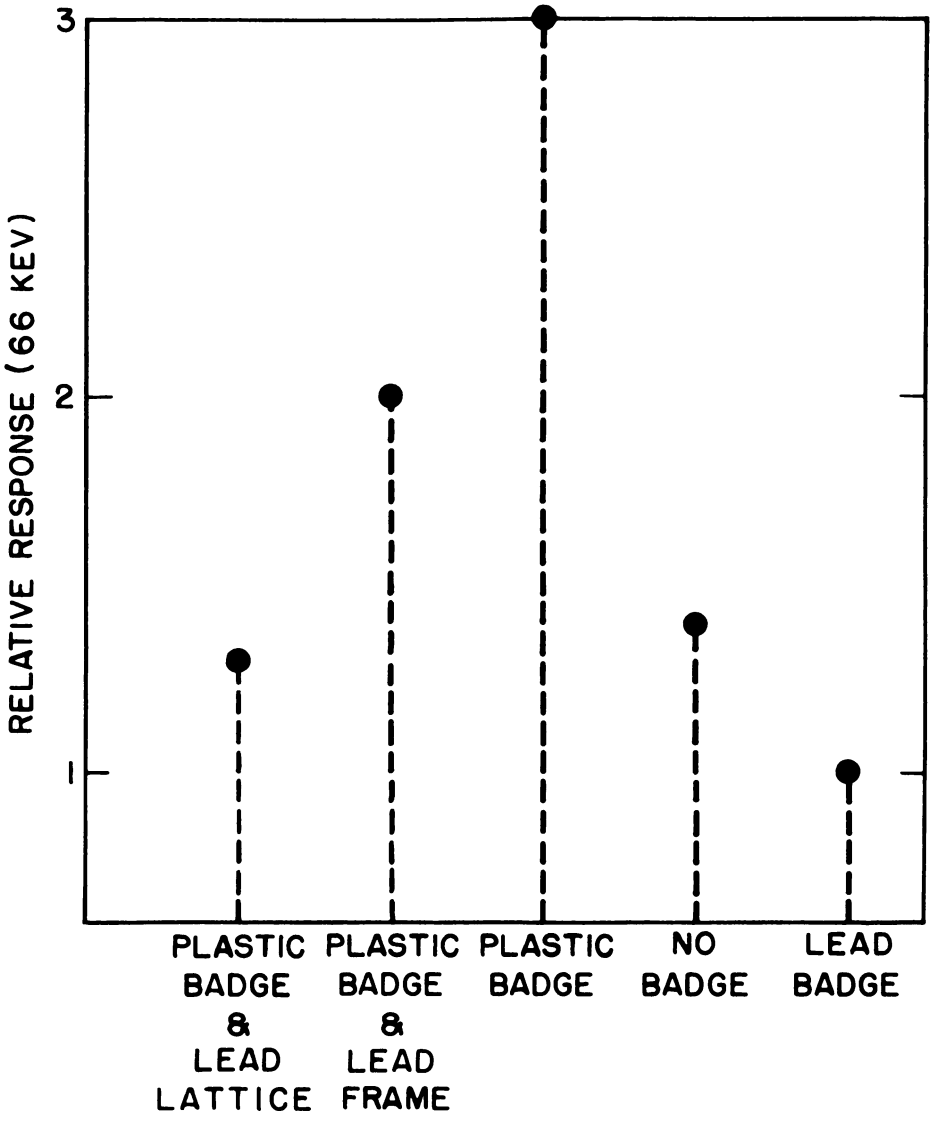

Fig. 6. The effect of badge scatter on the response of Du Pont 502 film filtered by copper plus a five-element filter.

no surrounding material, a response of 1.4 is obtained; that is, 40 per cent of the blackening is due to radiation not passing directly through the filter. When the same filter is placed in a plastic badge, the response increases to 3.0. Two methods of reducing the scatter in the plastic badge were tried. First the filter was surrounded by a lead frame, shown in Fig. 5b; with the lead frame the film response in the plastic badge decreased from 3 to 2. Second a lead lattice, or a sheet of 0.028 in. lead containing an opening for the filter, was placed between the plastic badge and film wrapper as shown in Fig. 5c; with the lead lattice the film response in the plastic badge decreased from 3 to 1.3.

The scattering effect is smaller at energies greater than 66 kev and larger at energies less than 66 kev; for example, almost all of the blackening observed under the filtered area at 40 kev is caused by radiation scattering in the plastic badge and entering the filtered area.

The Lead-Frame and Lead-Lattice Plastic Badges

Figure 3 shows that the Du Pont 502 film filtered by the 1 x 1 cm 0.04 in. plastic plus 0.02 in. copper plus five-element filter (described in Table III) in the plastic badge has an over-sensitivity of 2 in the low energy x-ray region. From the measurements shown in Fig. 6 it appeared that if the 0.04 in. plastic were removed and a lead frame were placed around the filter, the film response would be greatly improved.

A cycolac plastic film badge was constructed containing copper plus five-element filters surrounded by lead frames. The lead frames were 1.1 cm square(outside dimensions), and 0.165 cm thick with a 1.0 cm square hole. The lead-frame plastic film badge is shown in Fig. 5b.

The response of Du Pont 502 film filtered by the copper plus five-element filter in the lead-frame plastic badge is shown in Fig. 7, where the relative sensitivity is plotted versus the photon energy; the relative sensitivity has been set equal to 1 at 1250 kev. The film response lies within 0.7 to 1.2 from about 40 to 1250 kev. Below 100 kev the density under the filtered area is non-uniform with the edges darker than the central region. In the film response measurements in Fig. 7 the density was read in the center of the filtered area.

Also given in Fig. 7 is the Du Pont 502 film response measured with the same filter in the thick-lead badge shown in Fig. 5a. In the lead badge the film response falls off very sharply below about 80 kev. The two response curves in Fig. 7, both measured with the same film and filter but in different badges, show quite clearly that the type of badge employed to hold the film and filter has a significant effect on the film response in the low energy region. The relatively flat response obtained with the lead-frame plastic badge was achieved, in effect, by empirically adjusting the amount of radiation scattering into the filtered area. In addition, it is apparent that the relatively

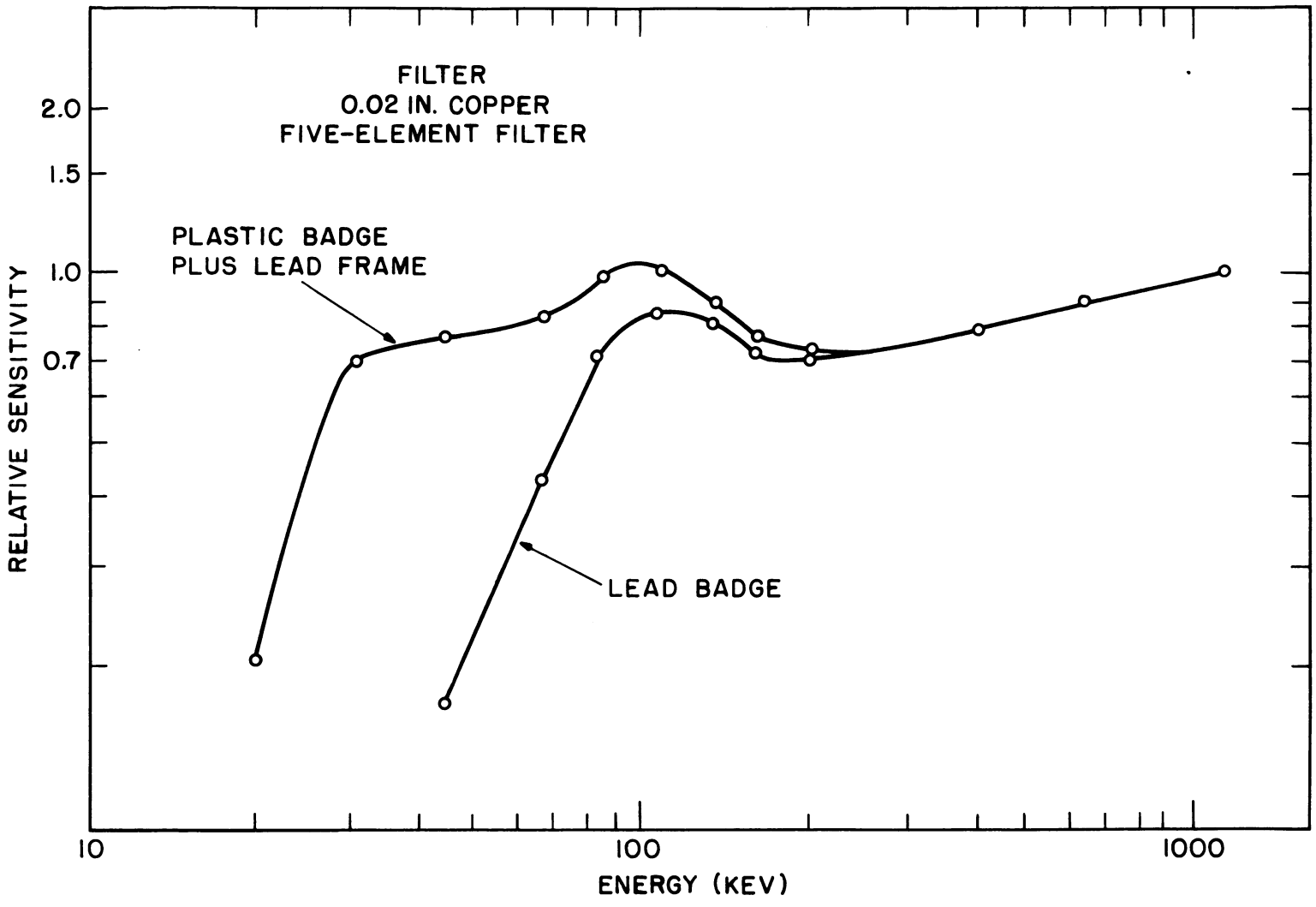

Fig. 7. Response of Du Pont 502 film filtered by copper plus a five-element filter in the lead-frame plastic badge and in the thick-lead badge.

flat response obtained earlier (Fig. 2) with the 1/2 x 1 in. copper plus multi-element filter in a plain plastic badge was entirely fortuitous, because the true film response of this filter is that measured in the thick-lead badge as shown in Fig. 7.

An investigation was made to determine why the film response of the copper plus five-element filter in the lead badge fell off so sharply in the low energy x-ray region. The absorption coefficients employed in the calculations which specified the amount of material to place in the filter were based on the theoretical values given in NBS Circular 583.[6] To check these coefficients, absorption measurements were made employing fluorescent sources, known amounts of filtration, and the free-air ionization chamber. These measurements indicated that the absorption coefficients given in NBS Circular 583 for elements with atomic numbers greater than 50 and energies below the K-edge of these elements were too low by as much as 50 per cent. Since the absorption coefficients appear in the exponent, this would result in errors as large as a factor of 10 in the calculations. About this time, a Supplement[9] to NBS Circular 583 was issued giving new absorption coefficients which agreed more closely with the coefficients measured with the fluorescent sources.

The amount of material required in the five-element filter was recalculated employing the new absorption coefficients. A new filter,

described in Table IV, was fabricated. The response of Du Pont 502 film filtered by 0.02 in. copper plus the new five-element filter in the thick-lead badge is shown in Fig. 8. The response is flat within 30 per cent from about 50 to 1250 kev.

The problem now was to achieve this response with the new filter in a lighter badge. Figure 6 shows that when a lead lattice, or a sheet of lead containing an opening for the filter, is placed between the plastic badge and film wrapper, the scatter into the filtered area is appreciably reduced. A cycolac plastic film badge, shown in Fig. 5c, was constructed with a 0.028 in. thick lead lattice. The Du Pont 502 film in this badge, filtered by 0.02 in. copper and the new five-element filter, gave a sensitivity of about 1.6 in the low energy region. The thickness of the copper filter was increased from 0.02 in. to 0.024 in. As Fig. 8 shows, the Du Pont 502 film response filtered by the 0.024 in. copper plus new five-element filter in the lead-lattice plastic badge was essentially the same as its response when filtered by the 0.02 in. copper plus new five-element filter in the thick-lead badge.

Again the original problem of obtaining a flat response film badge appeared to be solved. Both the lead-frame plastic and the lead-lattice plastic badges met the original requirements. The lead-frame plastic badge with the 0.02 in. copper plus old five-element filter (described in Table III) gave a Du Pont 502 film response flat within 30 per cent from

TABLE IV

THE NEW FIVE-ELEMENT FILM FILTER

Elements	Atomic Number	Amount of Element (g/cm^2)	Form of Element	K-edge Energy (kev)
Gadolinium	64	0.015	Gd_2O_3	50.229
Erbium	68	0.098	Er_2O_3	57.483
Tantalum	73	0.100	Ta powder	67.400
Gold	79	0.138	Au powder	80.713
Bismuth	83	0.081	Bi powder	90.521

Total amount of material including 3% paraffin binder = 0.445 g/cm^2.

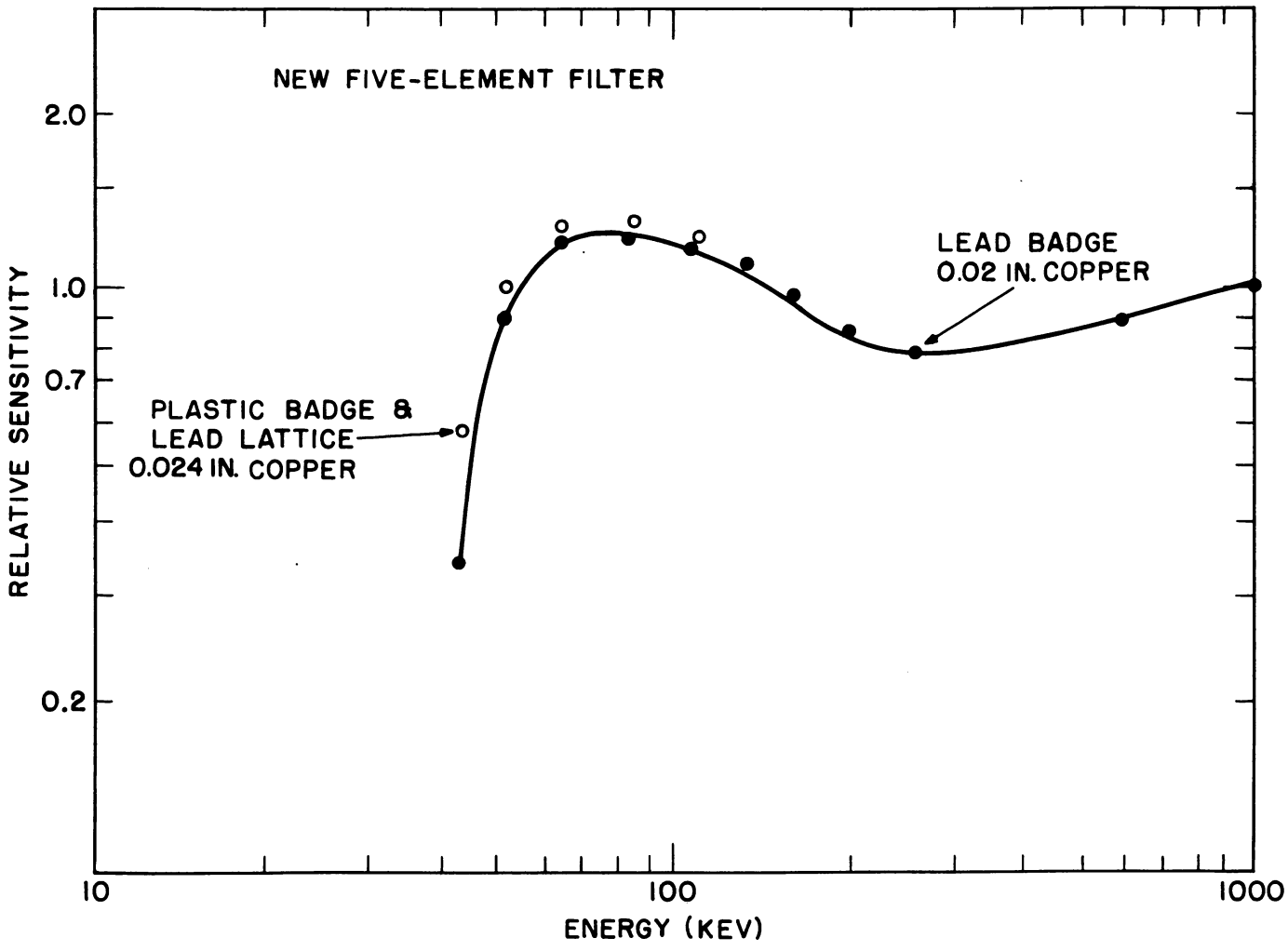

Fig. 8. Du Pont 502 film response in thick-lead badge with 0.02 in. copper plus a new five-element filter and in lead-lattice plastic badge with 0.024 in. copper plus the new five-element filter.

about 40 to 1250 kev. The lead-lattice plastic badge with the 0.024 in. copper plus the new five-element filter (described in Table IV) gave a Du Pont 502 film response flat within 30 per cent from about 50 to 1250 kev.

Both types of badges have disadvantages. At low energies the density under the filtered area is non-uniform in the frame badge and more uniform in the lattice badge. On the other hand, the lattice badge is more directionally dependent than the frame badge. At low energies and at an angle of incidence of 75 degrees, the film response of the lattice badge is low by about a factor of 10. When lead strips are added to the edges of the frame badge shown in Fig. 5b, the film response is directionally independent within 30 per cent. However, the directional dependence of the frame badge is appreciably affected by changes in its construction. For example, a frame badge was enlarged to include the NTA packet, lead identifying strips were placed inside the badge, and two more 1 x 1 cm filter areas were added to the badge; the response of this badge at low energies and at an angle of incidence of 75 degrees was low by a factor of 3. Thus the directional dependence of the frame type badge depends on the final badge design, but it will probably remain less dependent on direction than the lattice badge.

An attempt was made to determine whether the film response changed with the emulsion or batch number. The response of three different

emulsions of Du Pont 502 film, having expiration dates of January, March, and May 1960, was measured at 100 and 1250 kev and found to agree within 5 per cent. More significant, perhaps, was the measurement of the response of a Du Pont 502 film emulsion having an expiration date of July 1956; its response at 100 and 1250 kev was within 5 per cent of the response of the emulsions having the 1960 expiration date.

Response of Several Film Types in the Frame and Lattice Badges Measured in Air and on a Phantom

All the film badge development work described up to this time had been performed with Du Pont 502, a film used for personnel monitoring at Los Alamos for more than 10 years. Within a few days after the experimental work was completed, Du Pont announced that they were discontinuing the manufacture of 502 film.

Du Pont 508 and 555, Eastman Type II, and Ilford PM-1 films cover an exposure range similar to that of Du Pont 502. The response of all four film types was measured in the lead-frame and lead-lattice plastic badges. The results are shown in Figs. 9 and 10 for the frame and lattice badges, respectively. In both figures the relative sensitivity is plotted versus the photon energy, and the relative sensitivity has been set equal to 1 at 1250 kev.

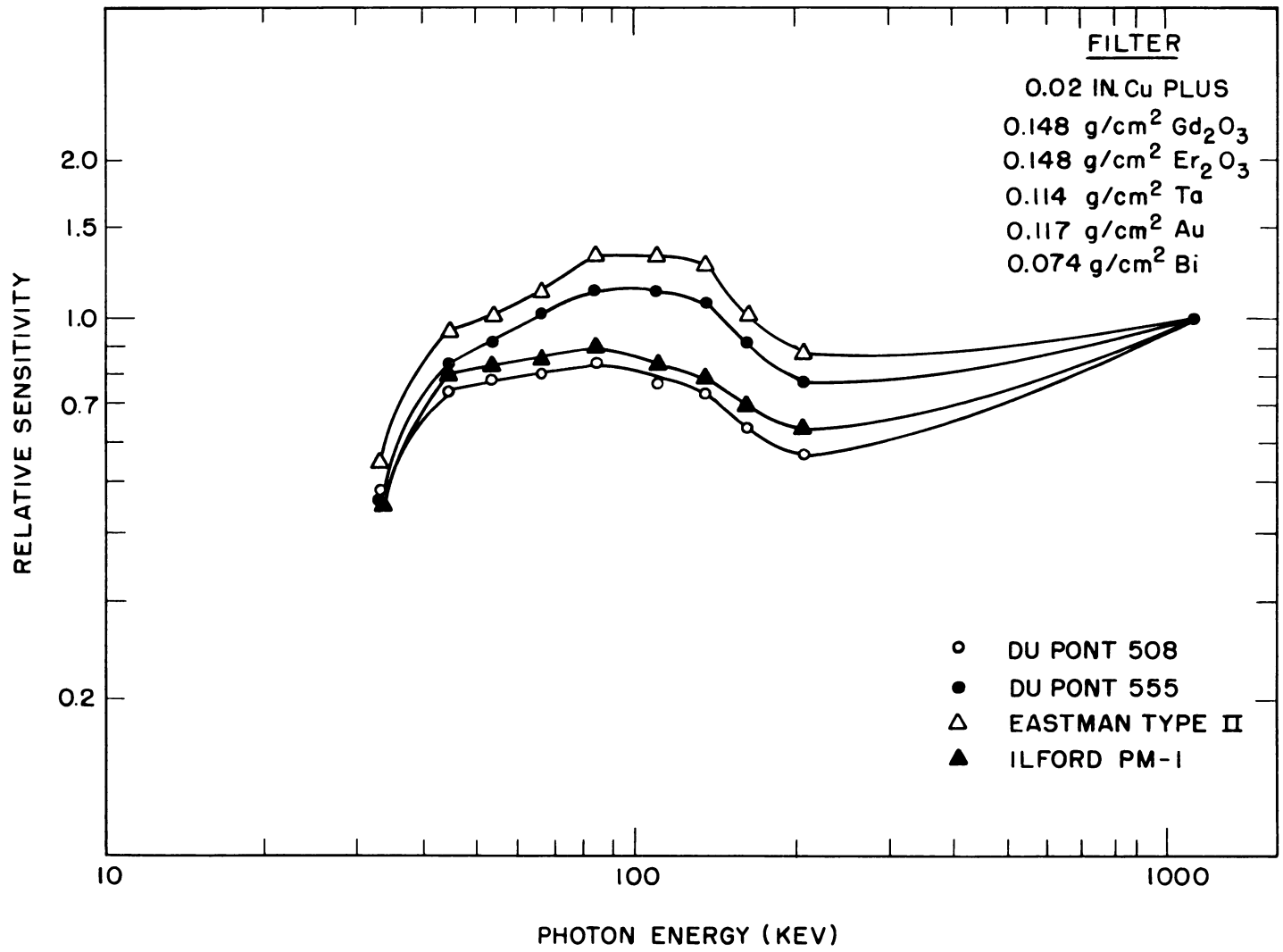

Fig. 9. Response of Du Pont 508 and 555, Eastman Type II, and Ilford PM-1 films in the lead-frame plastic badge.

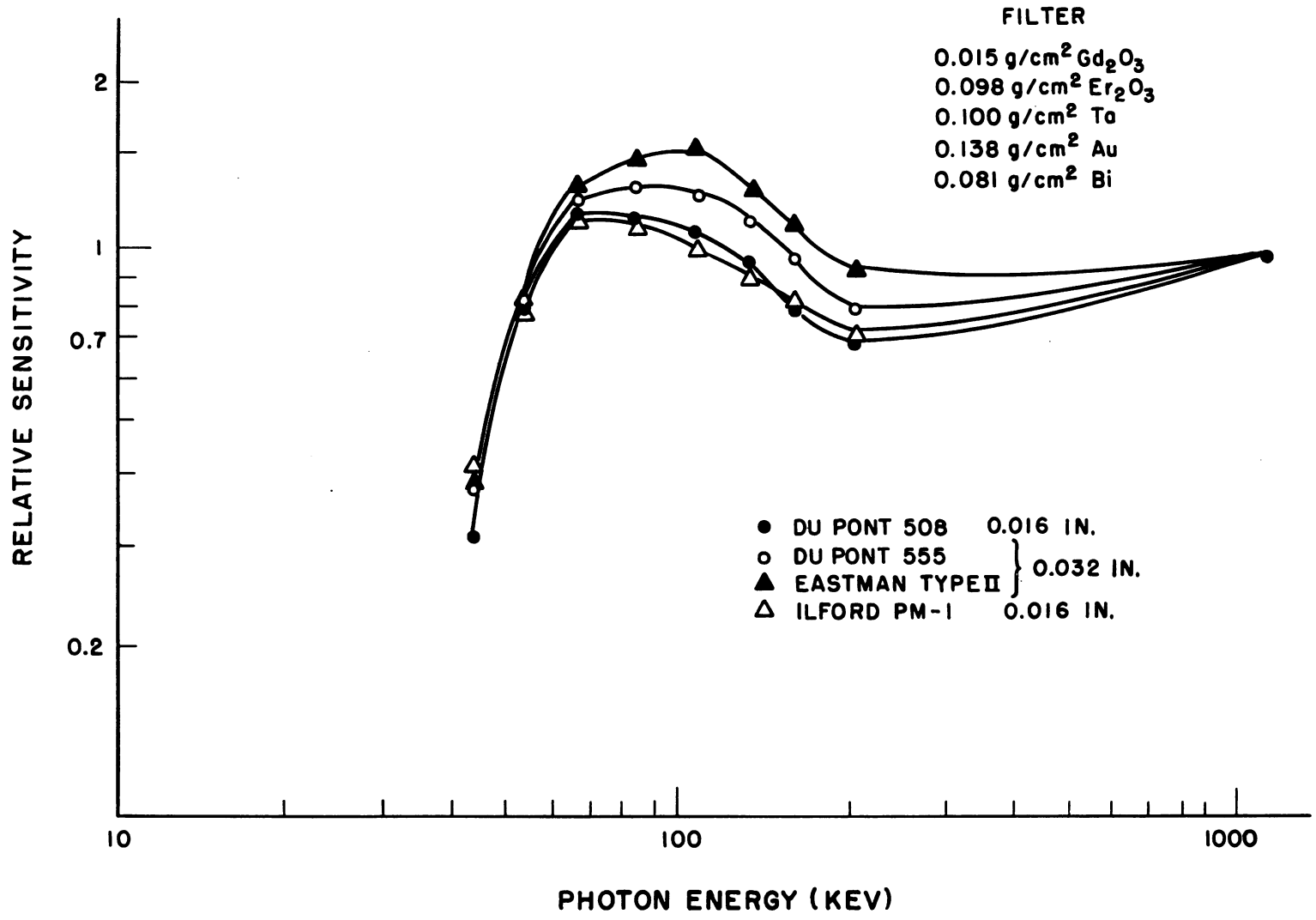

Fig. 10. Response of Du Pont 508 and 555, Eastman Type II, and Ilford PM-1 films in the lead-lattice plastic badge.

In the frame badge with the 0.02 in. copper plus old five-element filter, the film response fell within the following relative sensitivity limits from 40 to 1250 kev: Du Pont 508, 0.55 to 1.0; Du Pont 555, 0.7 to 1.1; Eastman Type II, 0.8 to 1.3; and Ilford PM-1, 0.6 to 1.0. The response of each film falls essentially within the limits of 30 per cent if the film is calibrated at an energy where the sensitivity is midway between the extreme sensitivity limits. Or the same result can be achieved by applying a correction factor to the 1250 kev Co^{60} calibration; correction factors of 0.77, 0.9, 1.05, and 0.8 would be applied to Du Pont 508, Du Pont 555, Eastman Type II, and Ilford PM-1 films, respectively.

To obtain a satisfactory response with each film type in the lattice badge, it was necessary to use two different thicknesses of copper with the new five-element filter. With Du Pont 508 and Ilford PM-1 films the copper thickness was 0.016 in., and with Du Pont 555 and Eastman Type II films the thickness was 0.032 in. The lead lattice was 0.028 in. thick.

The film response fell within the following relative sensitivity limits from 50 to 1250 kev: Du Pont 508, 0.65 to 1.2; Du Pont 555, 0.7 to 1.35; Eastman Type II, 0.7 to 1.5; and Ilford PM-1, 0.7 to 1.2. Again the response of each film falls within the limits of 30 per cent if the film is calibrated at an energy where the sensitivity is midway between the extreme limits or if the following correction factors are applied to the 1250 kev calibration: 0.95, 1.05, 1.2, and 0.95 to the

Du Pont 508, Du Pont 555, Eastman Type II, and Ilford PM-1 films, respectively.

Thus either the frame or the lattice badge can be used with Du Pont 508 and 555, Eastman Type II, and Ilford PM-1 films to measure personnel exposure to photons with an accuracy of 30 per cent over an energy range from about 50 to 1250 kev.

The effect of body scatter on the Du Pont 508 and 555 film response was measured in the frame and lattice badges. A water-filled 20 liter polyethylene jug was used to simulate the body. Both the lattice and frame badges gave essentially the same results. At 1250 kev the film response on the phantom was the same as in air, but at lower energies the response was greater on the phantom.

Figure 11 shows the response of Du Pont 508 and 555 films in the frame badge measured both in air and on the phantom. From 40 to 1250 kev the Du Pont 508 relative sensitivity limits are 0.55 to 1.0 in air and 0.6 to 1.1 on the phantom. Similarly, from 40 to 1250 kev the Du Pont 555 limits are 0.7 to 1.1 in air and 0.8 to 1.3 on the phantom. As in air, the film response on the phantom falls within the limits of 30 per cent if the filter is calibrated at an energy where the sensitivity is midway between the extreme sensitivity limits.

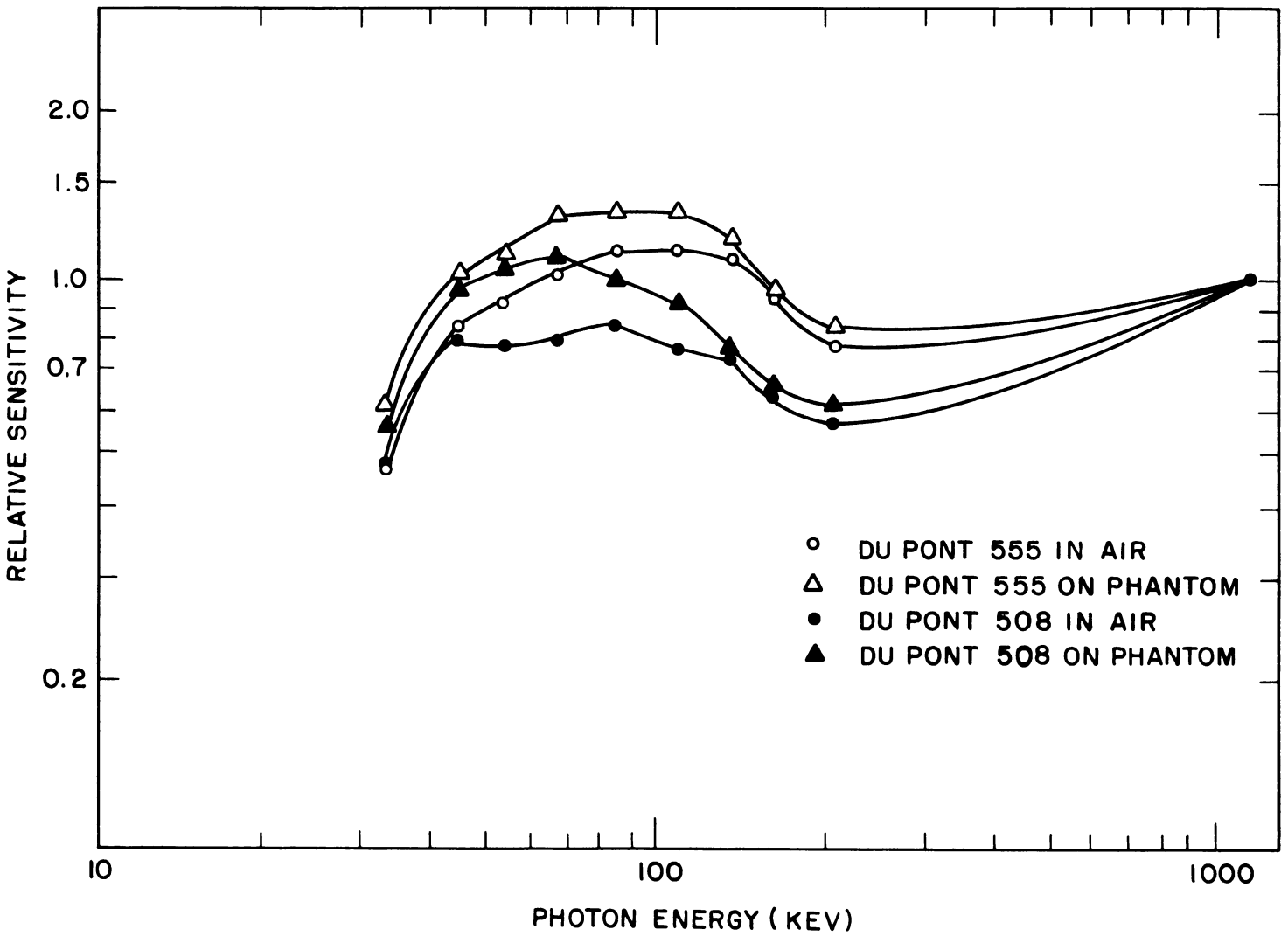

Fig. 11. Du Pont 508 and 555 film response measured with the lead-frame plastic badge in air and on a phantom.

The phantom was used to estimate the error due to body absorption when the badge is worn on the chest and a person is exposed from the back. Badges were exposed at the same distance from the 108 and 1250 kev sources with and without the phantom between the source and detector. The phantom reduced the exposure by a factor of 50 at 108 kev and a factor of 2.5 at 1250 kev.

RESPONSE OF THE BADGES TO NEUTRONS

Another requirement of the Los Alamos film badge was the capability of measuring thermal neutrons. Consequently, the frame and lattice badges were modified for this purpose. Frame and lattice badges were constructed as shown in Fig. 12 with three 1 x 1 cm filter areas. One area contained no filter to estimate beta exposure, the central area contained a filter to measure gamma exposure, and the third area contained a filter to measure both gamma and thermal neutron exposures. The badges were deepened to hold two film packets, an Eastman Type B and a Du Pont Type 555 film.

Figure 13 shows the photon response of the Du Pont 555 film measured in air in the modified frame badge. The film response under the filter specified in Table III in the modified frame badge falls off more rapidly in the low energy region than it did in the original frame badge. However, since the relative sensitivity limits are 0.6 to 1.1 from 50 to 1250 kev, the response falls within the limits of 30 per cent if the film is calibrated at an energy where the sensitivity is midway between the extreme limits or if a correction factor of 0.85 is applied to the Co^{60} calibration curve. The response of Du Pont 508,

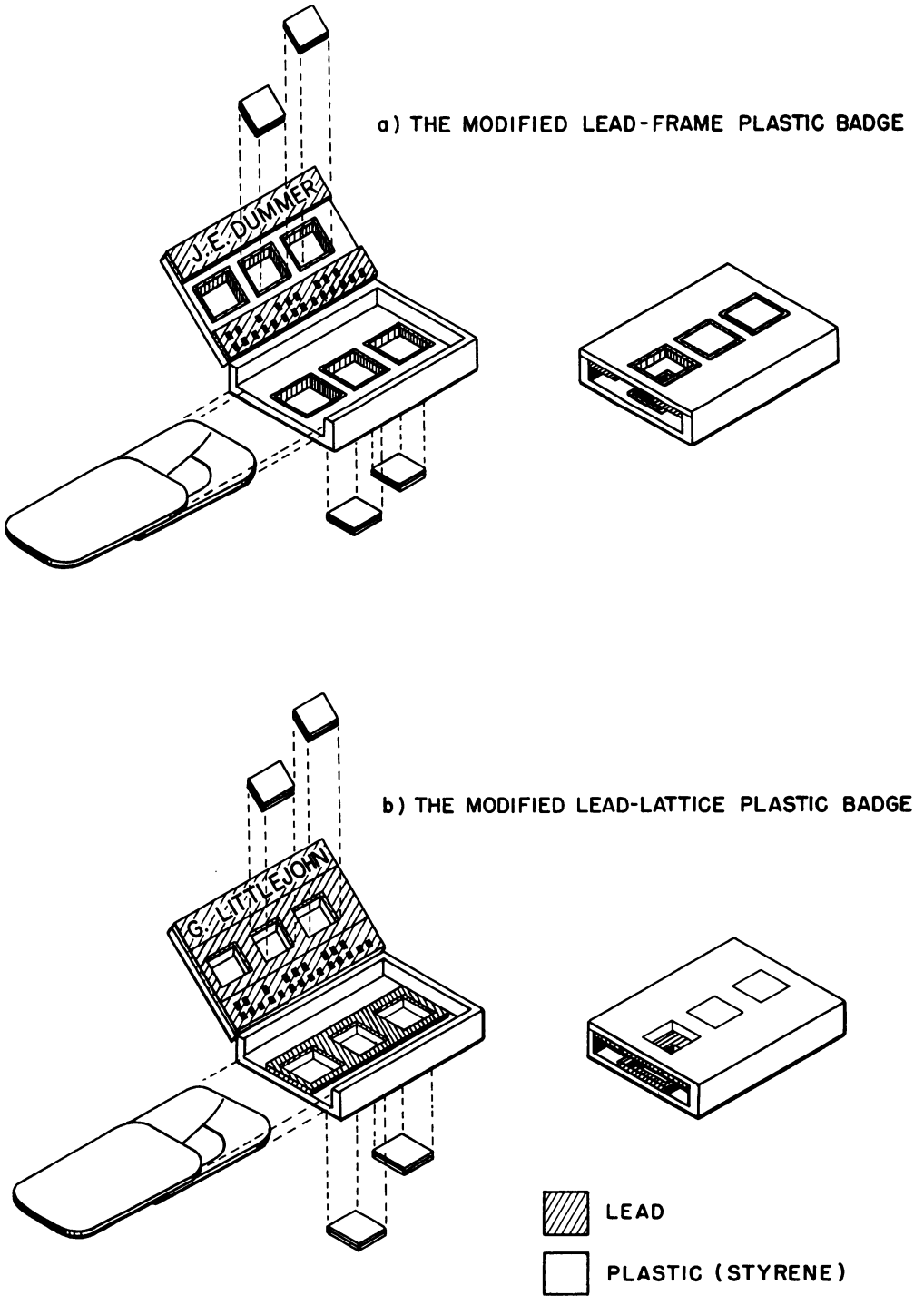

Fig. 12. The modified lead-frame and lead-lattice plastic film badges.

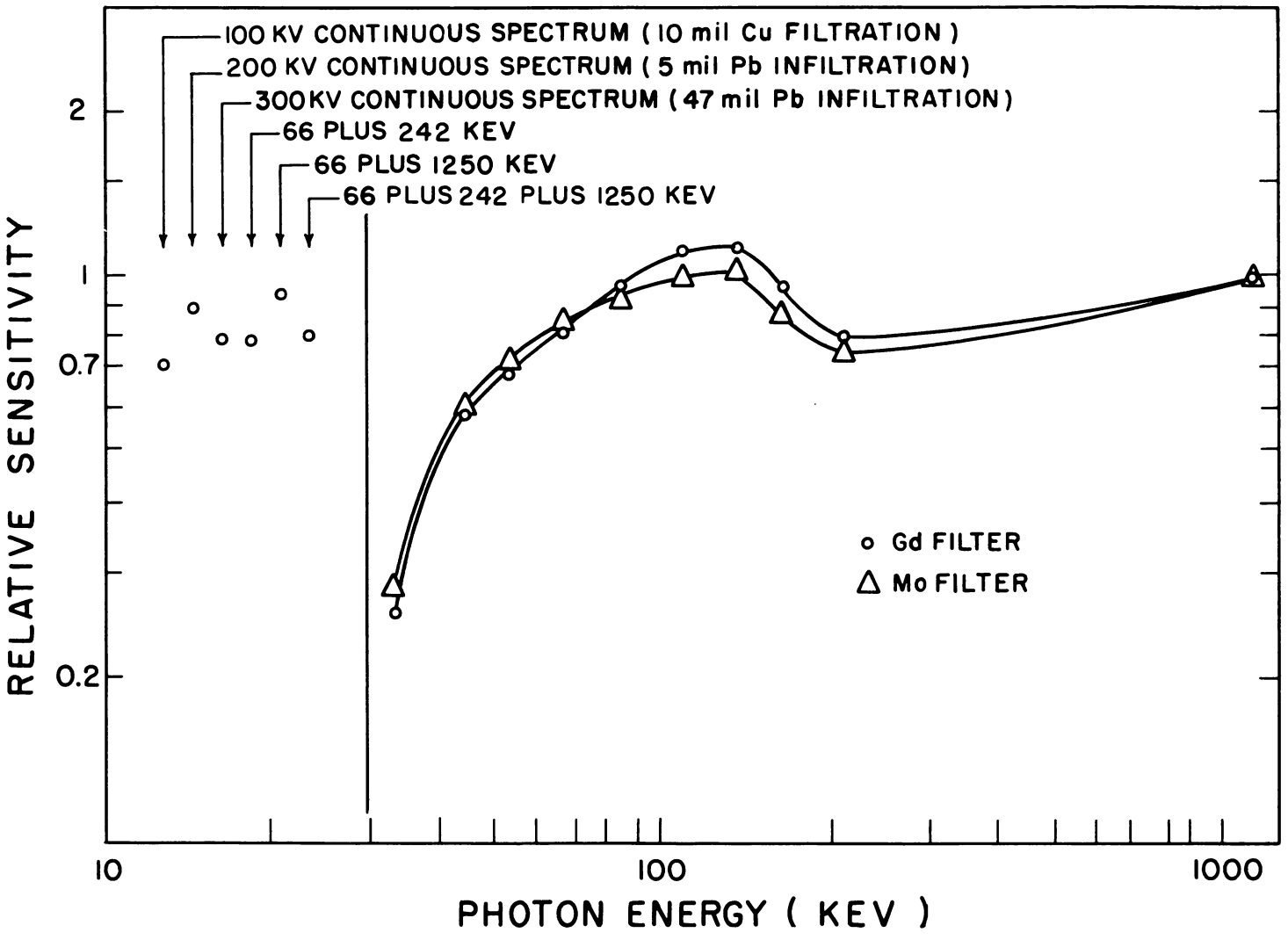

Fig. 13. Photon response of Du Pont 555 film in a modified frame badge with gadolynium and molybdenum filters.

Eastman Type II, and Ilford PM-1 film in the modified frame badge also falls within the limits of 30 per cent from 50 to 1250 kev when appropriate correction factors are applied to the Co^{60} calibration. In the modified lattice badge with the filter specified in Table IV, the response of all four film types was the same as in the original badge, within 5 per cent.

Also shown in Fig. 13 is the response of Du Pont 555 film in the modified frame badge to continuous spectrum radiation and to equal proportions of mixed monochromatic radiation. The kilovoltage and filtration employed with the continuous spectrum sources and the energy of the monochromatic sources are listed in the figure. The points fall within relative sensitivities of 0.7 to 0.95.

The response of the modified frame and lattice badges to both thermal and fast neutrons was measured and a method of evaluating thermal neutron exposure with these badges was devised. Since both badges gave similar results, only the measurements obtained with the frame badge are presented. In the discussion that follows, when a filter is described it will be understood that identical filters were placed on both the front and back of the badge.

Thermal Neutrons

The filter employed in the frame badge to obtain a flat x-ray response consisted of 0.02 in. copper plus the five elements described

in Table III; this filter will now be called the "gadolinium filter." Gadolinium, one of the elements in the filter, has a thermal neutron cross section of about 5×10^4 barns. Upon capturing a neutron, gadolinium emits gamma rays with energies of several Mev which, of course, produce film blackening. Thus a significant thermal neutron film response was obtained with the gadolinium filter. Two methods of utilizing this response to measure personnel exposure to thermal neutrons were devised.

The first method consisted of using two gadolinium filters one of which was surrounded by a Li^6F cup. Powder metallurgy techniques were employed to fabricate the 0.03 in. thick cups. Since the Li^6 thermal neutron cross section is about 10^3 barns, and the absorption of thermal neutrons in Li^6 is not accompanied by the emission of gamma rays, the Li^6F cups significantly reduced the thermal neutron film response with the gadolinium filter. The difference in blackening between the Li^6F covered gadolinium filter and the uncovered gadolinium filter was large enough to be used as a measure of the thermal neutron exposure. In addition, the Li^6F cups did not significantly affect the response of the film to photons. However, the Li^6F cups were somewhat fragile, and their incorporation in the badge was difficult.

Consequently, a second method was devised which gave results similar to that obtained with the Li^6F cups. Again two filters were

used: a gadolinium filter and one similar to it but with the gadolinium replaced by 0.01 in. of molybdenum. The molybdenum was sandwiched between the copper and multi-element filter; this combination will be called the molybdenum filter. Since the thermal neutron cross section of molybdenum (about 3 barns) is low compared to that of gadolinium, the thermal neutron film response with the molybdenum filter is lower than that with the gadolinium filter. The difference in blackening between the filters is large enough to be used as a measure of thermal neutron exposure.

Figure 13 shows that the x-ray response of Du Pont 555 film with the molybdenum filter is similar to that obtained with the gadolinium filter. However, between 80 and 200 kev, the gadolinium filter has about a 15 per cent greater film response than the molybdenum filter; thus an x-ray exposure could be mistaken for a thermal neutron exposure. This difficulty would be avoided by not reporting thermal neutron exposures unless the gadolinium filter exposure exceeded the molybdenum filter exposure by more than 15 per cent. Visual inspection of the film aids in determining whether the film has been exposed to thermal neutrons. When the film badge is exposed to thermal neutrons, the blackening spreads beyond the edges of the filter; this spreading has been observed only with neutron exposures.

The response of the film badges to thermal neutrons was measured with the thermal neutron beam of the Los Alamos Homogeneous Reactor. As shown in Fig. 14, badges were placed one foot from the graphite stringers both in air and on a one cubic foot block of polyethylene, which presumably simulates the thermal neutron scattering of the human body. Exposure times were controlled by an electrically operated boron shutter. The cadmium ratio, a measure of the number of thermal neutrons to the number of higher energy neutrons in the beam, is about 10^4.

Films exposed to the thermal neutron beam are blackened by a variety of sources.[10] As previously explained, the greater density observed under the gadolinium filter is due to the n,γ reaction in the gadolinium. However, a portion of the blackening under the gadolinium filter and all the blackening observed under the molybdenum filter is caused by other neutron interactions in the filter and film and by inherent gamma rays. The following interactions are probably the main contributors to the film blackening: the n,γ reaction in erbium (about 1.7×10^2 barns) and in gold (about 10^2 barns); and the gamma and beta rays associated with the neutron activation of the 18 min bromine, the 24 sec and 2.3 min silver, and the 5 min and 13 hr copper. The bismuth shield surrounding the reactor sphere absorbs most of the gamma rays emitted directly by the reactor, but high energy gamma rays are produced by neutron capture in the graphite stringers.

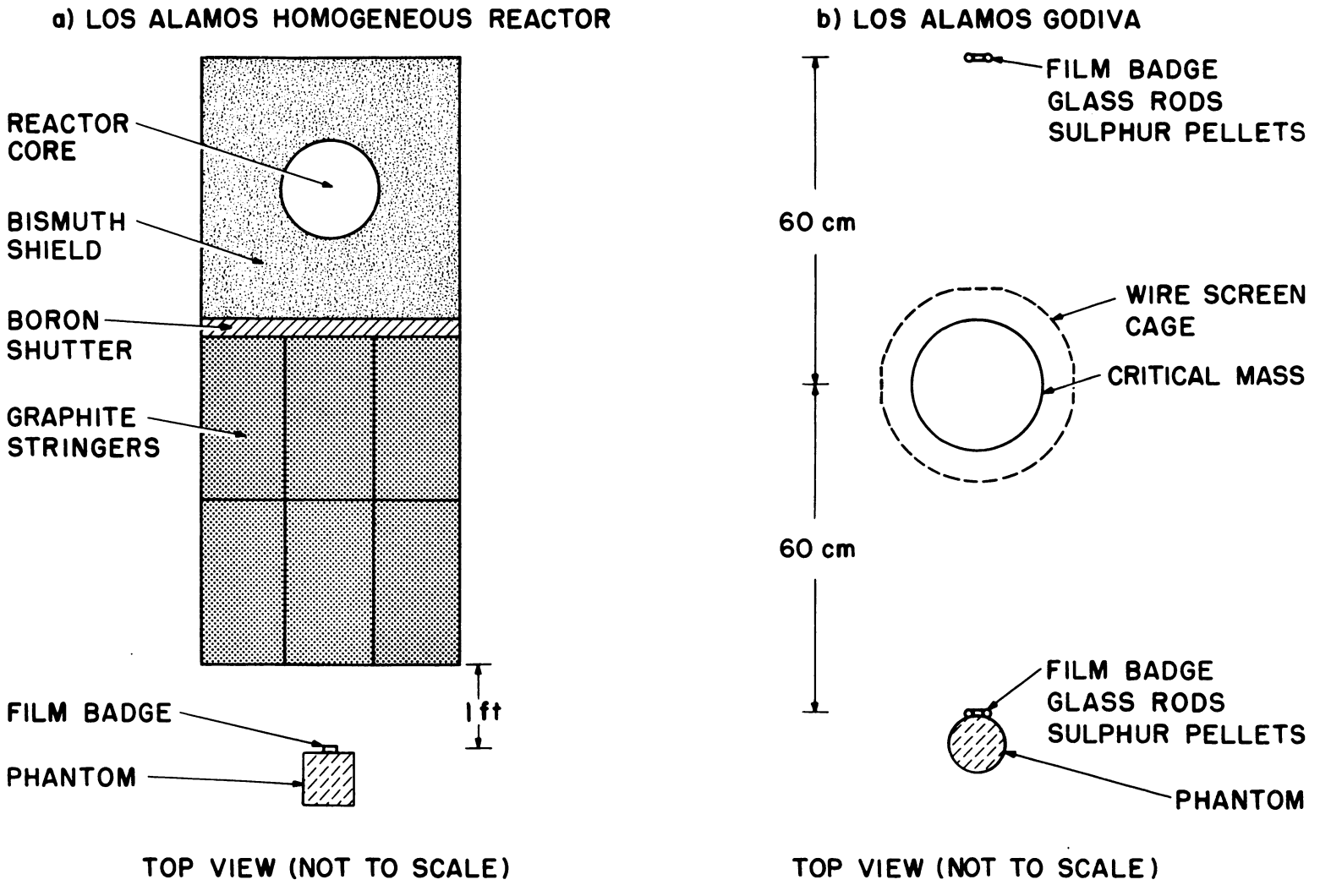

Fig. 14. Location of film badges exposed to (a) Los Alamos Homogeneous Reactor and (b) Godiva.

The gamma radiation produced by neutron capture in the graphite stringers was measured by completely surrounding a film in its wrapper by a layer of Li^6F powder thick enough to absorb all the thermal neutrons. When the Li^6F surrounded badges were exposed to a total flux of 10^9 th n/cm^2, the film densities corresponded to the following Co^{60} exposures: 0.25 r for badges located in air, and 0.33 r for badges located on the phantom. Since the films were shielded from the effects of thermal neutrons, the blackening observed is attributed to the inherent gamma radiation. In this report it will be assumed that the RBE for thermal neutrons is 3, which means that a flux of 10^9 th n/cm^2 corresponds to about 1 rem. Thermal neutron fluxes were measured by counting the activity of gold foils.

Figure 15 shows the thermal neutron response of the Du Pont 555 film in the frame badge with the gadolinium and molybdenum filters when exposed in air. The net density measured under the filters is plotted in the figure versus the total thermal neutron plus inherent gamma-ray exposure in terms of rem plus r. Also plotted in Fig. 15 is the Du Pont 555 Co^{60} calibration curve measured under the gadolinium filter in the frame badge; within 3 per cent, the same Co^{60} calibration curve is obtained with the molybdenum filter. The gadolinium points measured in the thermal neutron plus inherent gamma radiation exposures lie above the Co^{60} calibration curve, and the molybdenum points below the Co^{60} curve.

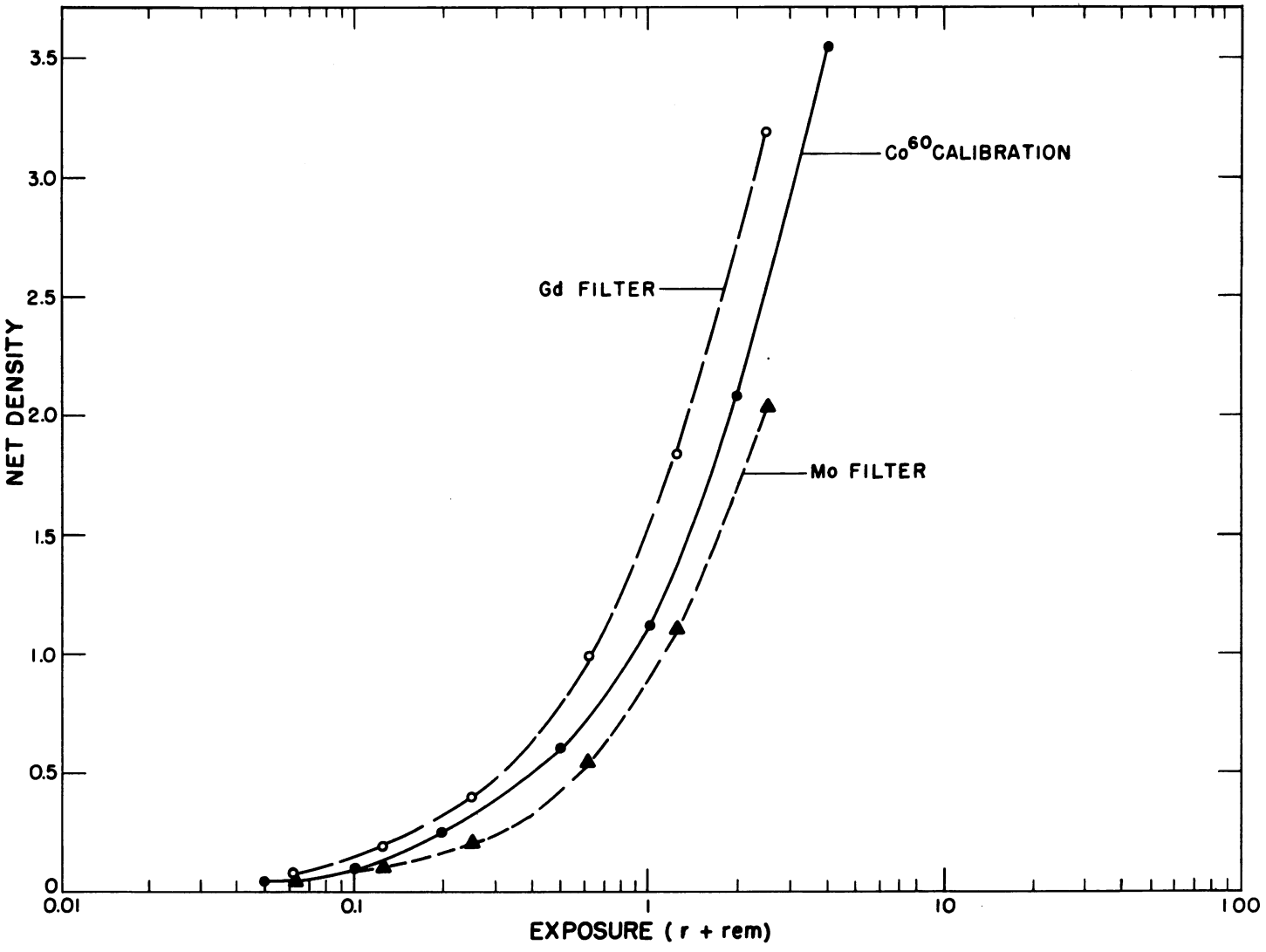

Fig. 15. Response to thermal neutrons of Du Pont 555 film in the modified lead-frame badge.

With the data shown in Fig. 15, the Co^{60} gamma ray to thermal neutron exposure ratio for the gadolinium filter may be calculated from the following equation:

$$E_{Gd} = E_{\gamma}F_{\gamma} + E_{n}F_{n,Gd} \quad (1)$$

where E_{Gd} is the Co^{60} exposure in r corresponding to the density under the gadolinium filter, E_{γ} is the inherent gamma radiation exposure in r, F_{γ} is the response of the film to the inherent gamma radiation exposure, E_{n} is the thermal neutron exposure in rem, and $F_{n,Gd}$ is the response of the gadolinium filtered film to thermal neutrons. With F_{γ} taken to be 1, $F_{n,Gd}$ was 1.43 r/rem.

Similarly, the Co^{60} gamma ray to thermal neutron exposure ratio for the molybdenum filter may be calculated from the following equation:

$$E_{Mo} = E_{\gamma}F_{\gamma} + E_{n}F_{n,Mo} \quad (2)$$

where E_{Mo} is the Co^{60} exposure in r corresponding to the density under the molybdenum filter, E_{γ} is the inherent gamma radiation exposure in r, F_{γ} is the response of the film to the inherent gamma radiation exposure, E_{n} is the thermal neutron exposure in rem, and $F_{n,Mo}$ is the response of the molybdenum filtered film to thermal neutrons. With F_{γ} taken to be 1, $F_{n,Mo}$ was 0.70 r/rem.

With the constants $F_{n,Gd}$ and $F_{n,Mo}$ determined, the thermal neutron exposure to the badge can be calculated by combining equations (1) and (2):

$$E_n = \frac{E_{Gd} - E_{Mo}}{F_{n,Gd} - F_{n,Mo}} = \frac{E_{Gd} - E_{Mo}}{1.43 - 0.70} = \frac{E_{Gd} - E_{Mo}}{0.73} \qquad (3)$$

The gamma radiation exposure can then be calculated from either equation (1) or (2).

The film badges and gold foils exposed to the thermal neutron beam at a distance of 1 meter from the face of the graphite on the phantom read 56 per cent higher than those exposed in air for the same flux. Thus, 56 per cent of the thermal neutrons incident on the phantom are reflected back and recorded by the badges and foils. Hence, when evaluating personnel exposure to thermal neutrons, the film badge reading should be divided by 1.56 to correct for body neutron reflection.[11]

To obtain an estimate of the accuracy of this method of evaluating thermal neutron exposure in the presence of gamma radiation, film badges were exposed to different proportions of thermal neutron and gamma radiation. Table V gives the measured thermal neutron, inherent gamma radiation, Co^{60} gamma radiation, total gamma radiation, and total thermal neutron plus gamma radiation exposure received by the badges. It also gives the calculated thermal neutron, total gamma radiation, and total thermal neutron plus gamma radiation exposure. As may be seen from the ratios listed in Table V, the calculated and measured values of the total thermal neutron plus gamma radiation exposures agree within 29 per cent.

TABLE V

EXPOSURE EVALUATION OF BADGES EXPOSED TO DIFFERENT PROPORTIONS OF THERMAL NEUTRONS AND GAMMA RADIATION

Measured					Calculated			
Th n (rem)	Inherent γ (r)	$Co^{60}\gamma$ (r)	Total γ (r)	Total Th n+γ (r+rem)	Th n (rem)	Total γ (r)	Total Th n+γ (r+rem)	Total Th n+γ (meas/calc)
0.02	0.005	0.02	0.025	0.045	0.000	0.035	0.035	1.29
0.05	0.012	0.02	0.032	0.082	0.036	0.037	0.073	1.12
0.10	0.025	0.02	0.045	0.145	0.085	0.054	0.139	1.04
0.20	0.050	0.02	0.070	0.270	0.216	0.051	0.267	1.01
0.50	0.125	0.02	0.145	0.645	0.550	0.089	0.639	1.01
1.00	0.250	0.02	0.270	1.270	0.917	0.340	1.257	1.01
0.02	0.005	0.05	0.055	0.075	0.012	0.053	0.065	1.15
0.05	0.012	0.05	0.062	0.112	0.026	0.087	0.113	0.99
0.10	0.025	0.05	0.075	0.175	0.082	0.093	0.175	1.00
0.20	0.050	0.05	0.100	0.300	0.202	0.098	0.300	1.00
0.50	0.125	0.05	0.175	0.675	0.547	0.098	0.645	1.05
1.00	0.250	0.05	0.300	1.300	0.848	0.410	1.258	1.03
0.02	0.005	0.10	0.105	0.125	0.012	0.097	0.110	1.14
0.05	0.012	0.10	0.112	0.162	0.048	0.109	0.157	1.03
0.10	0.025	0.10	0.125	0.225	0.097	0.125	0.222	1.01
0.20	0.050	0.10	0.150	0.350	0.205	0.137	0.342	1.02
0.50	0.125	0.10	0.225	0.725	0.502	0.203	0.705	1.03
1.00	0.250	0.10	0.350	1.350	0.890	0.460	1.350	1.00
0.02	0.005	0.20	0.205	0.225	0.014	0.200	0.214	1.05
0.05	0.012	0.20	0.212	0.262	0.073	0.186	0.259	1.01
0.10	0.025	0.20	0.225	0.325	0.096	0.231	0.327	0.99
0.20	0.050	0.20	0.250	0.450	0.190	0.254	0.444	1.01
0.50	0.125	0.20	0.325	0.825	0.520	0.287	0.807	1.02
1.00	0.250	0.20	0.450	1.450	0.930	0.450	1.380	1.05
0.02	0.005	0.50	0.505	0.525	0.027	0.501	0.528	0.99
0.05	0.012	0.50	0.512	0.562	0.055	0.522	0.576	0.97
0.10	0.025	0.50	0.525	0.625	0.082	0.563	0.645	0.97
0.20	0.050	0.50	0.550	0.750	0.192	0.586	0.778	0.96
0.50	0.125	0.50	0.625	1.125	0.506	0.645	1.151	0.98
1.00	0.250	0.50	0.750	1.750	1.053	0.710	1.763	0.99
0.02	0.005	1.00	1.005	1.025	0.041	1.002	1.043	0.98
0.05	0.012	1.00	1.012	1.062	0.055	1.041	1.096	0.97
0.10	0.025	1.00	1.025	1.125	0.096	1.083	1.179	0.95
0.20	0.050	1.00	1.050	1.250	0.260	0.988	1.248	1.00
0.50	0.125	1.00	1.125	1.625	0.548	1.067	1.615	1.01
1.00	0.250	1.00	1.250	2.250	1.250	0.940	2.190	1.03

Fast Neutrons

As mentioned previously, the Eastman Type B packet was to be included in the new Los Alamos badge to measure fast neutrons and to extend the photon exposure range. The Type B packet contains the NTA and the Fine Grain Positive film. The NTA film is used to measure 1 to 10 Mev neutrons over an exposure range of about 0.1 to 10 rem. The Fine Grain film is used to measure gamma-radiation exposures from about 20 to 1000 r. Since the Fine Grain film would be used in a criticality accident to measure the gamma-ray exposure, it was necessary to estimate the accuracy of the exposure evaluation when the film was exposed to both gamma rays and fast neutrons.

Accordingly, the Fine Grain film was exposed in the frame badge to the Godiva II critical assembly. Godiva II is a controlled critical assembly of bare enriched U^{235} surrounded by a wire screen cage and mounted on a triangular stand. As shown in Fig. 14, the film badges were exposed both in air and on the 20 liter water-filled polyethylene jug 60 cm from the center of the critical mass.

Glass dosimeter rods in $Li^{6}F$ cans and sulphur pellets were exposed with the badges. Since the glass rods were shielded from thermal neutrons by the $Li^{6}F$ cans and their response to fast neutrons is known to be 0.7 per cent[12] in terms of rads, the glass rod measurement of the gamma-ray exposure was assumed to be correct. Sulphur pellets were used to measure

the number of neutrons above 2.5 Mev in energy. From the number of neutrons measured above 2.5 Mev, the total number of neutrons emitted by the Godiva can be estimated by assuming a known neutron spectrum;[13] conversion to rads can then be made by using first collision theory and a conversion factor of 2.4×10^{-9} rad/n/cm^2.

To determine whether the response of the film to fast neutrons was rate dependent, the detectors were exposed to radiation from 8.5×10^{15} fissions in two separate runs. In the first run the radiation was delivered in a "burst" lasting about 10^{-4} sec; the second run was a "steady state" condition lasting about 10^{2} sec. Thus the total exposure was the same in both runs, but the exposure rate in the burst was higher by a factor of 10^{6}.

The results of the Godiva measurements are given in Table VI. From the sulphur pellets it was estimated[13] that the detectors in air were exposed to about 900 rads of fast neutrons. On the phantom the sulphur detectors read about 12 per cent less than they did in air. Gamma-ray exposures recorded by the glass rods were evaluated[12] from a Co^{60} calibration. Gamma radiation and apparent thermal neutron exposures recorded by the film badges were evaluated from a Co^{60} calibration and the gadolinium and molybdenum filter exposure differences, according to the method described in the previous section on thermal neutrons.

TABLE VI

RESULTS OF GODIVA FILM BADGE MEASUREMENTS

Instrument Location	Godiva II Operation	Total* Fast Neutron Exposure (rad)	Glass Rod Gamma-Ray Exposure (r)	Film Badge Gamma-Ray Exposure (r)	Film Badge Thermal Neutron Exposure (rem)
In air	Burst	900	90	135	0
In air	Steady State	900	100	125	7.5
On phantom	Burst	800	110	195	44
On phantom	Steady State	800	125	210	65

* Estimated from activation of sulphur pellets.

The apparent thermal neutron evaluation appears to be exposure-rate dependent. Both in air and on the phantom the exposure is higher for the steady state run than for the burst. As expected, the film badge records a much higher thermal neutron exposure on the phantom than in air. Fast neutrons are thermalized throughout the phantom and diffuse back to the film badge, giving an indication of more than a factor of 10 over the thermal neutron exposure measured in air.

Table VI shows that the film badges read the gamma-ray exposure 25 to 50 per cent higher in air and about 70 per cent higher on the phantom than do the glass rods. Film badges exposed to the burst and steady state conditions agree within 10 per cent in their exposure evaluation, indicating that the gamma radiation evaluation for these conditions is not significantly exposure-rate dependent.

The purpose of these measurements was to estimate the accuracy of the film-badge gamma-radiation evaluation in case of a criticality accident. If the accident were to occur under conditions similar to those of the Godiva experiment, then the film-badge gamma-radiation evaluation would be high by 70 per cent. But the accuracy would depend upon the proportion of gamma to fast neutron radiation; if the proportion of gamma radiation were to increase, the relative fast neutron effect on the film response would decrease and the accuracy of the gamma radiation exposure evaluation would improve. In the Godiva

measurements the fast neutron exposure to the phantom in the steady state run was about 5600 rem (assuming an RBE of 7) and the gamma-radiation exposure was 125 rem (assuming an RBE of 1). Thus, the gamma-radiation exposure was about 2 per cent of the fast neutron exposure. If moderating material were placed between the critical mass and the film badge, the proportion of gamma to fast neutron radiation could increase by more than an order of magnitude. Under these conditions the gamma-radiation evaluation error would be less than 70 per cent.

SUMMARY

A description has been given of the experimental work leading to the development of flat roentgen response film badges containing multi-element filters.

Three types of sources were used to measure the film response: fluorescent x rays from 30 to 100 kev, heavily filtered direct x-ray beams from 100 to 250 kev, and isotope gamma rays from 250 to 1250 kev. Beam uniformity, spectrum purity, and exposure-rate measurements were made for each type of source.

The response of unfiltered Du Pont 502 film was 25 times greater to 40 kev x rays than to 1250 kev γ rays. Calculations indicated that a filter consisting of several elements with K-edges evenly spaced from 40 to 90 kev could reduce the energy dependence of the film within acceptable limits. Multi-element filters were placed in cycolac plastic film badges. The measured filtered film response was not in agreement with the calculated response, partially because of fluorescent radiation produced in the filter. A satisfactory film response was obtained when

copper was placed between the multi-element filter and the film to reduce the effects of fluorescent radiation.

When electron equilibrium plastic was inserted between the film and multi-element filter, the film response increased in the low energy region; the film response also increased when the size of the filter was reduced. In addition, the blackening in the filtered area was non-uniform, and the film badge was not as directionally dependent as calculation indicated. Measurements with a thick-lead badge showed that these effects were due to radiation scattering in the plastic badge and not to radiation passing directly through the filter. Two plastic film badges were developed containing either lead frames or lead lattices to reduce the amount of radiation scattering into the filtered area.

The lead-frame badge contains a multi-element filter (gadolinium, erbium, tantalum, gold, and bismuth) and a 0.02 in. copper filter. The response of Du Pont 502, 508, and 555, Eastman Type II, and Ilford PM-1 films in the badge is flat within 30 per cent from 40 to 1250 kev. The badge is directionally independent within 30 per cent over this energy region, but the density under the filtered area at low energies is non-uniform, the edges being darker than the central region.

The lead-lattice badge contains a multi-element filter (same elements as in the frame badge, but in different proportions) and a copper filter

whose thickness varies with the film type. In this badge the response of the same films listed above is flat within 30 per cent from 50 to 1250 kev. This badge is directionally dependent at low energies, and the density under the filtered area is uniform.

The following modifications were made in the frame and lattice badges: they were enlarged to hold a high-range gamma-radiation and fast-neutron film packet; lead strips with name and binary perforations were placed in the badge to identify the person wearing the badge; and two additional filter openings were added to the badge for purposes of evaluating thermal neutrons and beta radiation. These modifications did not alter the photon response of the lattice badge; however, the frame badge showed a greater directional dependence and it was now flat within 30 per cent above 50 instead of 40 kev.

A method of evaluating thermal neutrons was devised using two multi-element filters, the first containing gadolinium and the second substituting molybdenum for gadolinium. The response of these filters in the frame and lattice badges was measured both in air and on a phantom using the Los Alamos Homogeneous Reactor thermal neutron beam. On the phantom the film badge response was higher than in air by a factor of 1.56. The Co^{60} gamma ray to thermal neutron response of the gadolinium filtered and the molybdenum filtered film was 1.43 and 0.70 r/rem, respectively.

An estimate was made of the accuracy of the gamma exposure evaluation when the film is exposed to both gamma and fast neutron radiation. Film badges exposed to the Godiva critical assembly read as much as 70 per cent higher than glass rods exposed at the same time and location.

APPENDIX

SOURCES USED TO MEASURE THE FILM RESPONSE

To obtain the true energy response of the film it must be calibrated with x- or gamma-ray sources which are as nearly monochromatic as possible. Three types of sources were used to cover the energy range of 20 to 1250 kev. Fluorescent sources were used from 20 to 100 kev; heavily filtered direct x-ray beams were used from 100 to 250 kev; and the gamma rays from isotopes were used from 250 to 1250 kev.

Fluorescent Sources

Fluorescent rays are monochromatic x rays which are emitted by a substance when irradiated with x rays having greater energies than the binding energies of the electrons in the substance. When the primary x rays interact with a substance, they lose a portion of their energy, ejecting electrons from the atoms which are left in an excited state; the ionized atoms return to a normal state by liberating energy in the form of fluorescent radiation.

The two most prominent types of fluorescent x rays are the K- and L-lines. The L-lines are much less penetrating than the K-lines and in all cases sufficient thickness of aluminum was used to absorb them. There are four monochromatic K-lines; they are the $K\alpha_1$, $K\alpha_2$, $K\beta_1$, and $K\beta_2$, and their relative intensities are about 1.0, 0.5, 0.25, and 0.05, respectively.[14] The energy of each of these lines for several elements

between 47 and 92 is given in Table VII together with the weighted average energy for each element.

However, the purity of the fluorescent source is also affected by scattered radiation. When a substance is placed in a continuous spectrum x-ray beam, not only is fluorescent radiation produced, but also the primary x rays are scattered from the substance. The direction and energy of the primary rays are altered in passing through the substance; the energy of the scattered radiation is continuous but somewhat less penetrating than the primary x-ray spectrum. In order to have as pure a source as possible, the ratio of fluorescent to scattered radiation must be maximized.

The ratio of fluorescent to scattered radiation is affected by several factors. The most important of these are the thickness of the radiating element placed in the x-ray beam, the kilovoltage of the primary x-ray beam, the angle of the radiator with respect to the primary beam, and the location of the detector with respect to the primary beam. A program was developed for evaluating the ratio of fluorescent to scattered radiation using the IBM 704 calculating machine. The results of the program are too long to describe here, but it will be made the subject of a separate report. However, on the basis of these calculations it was decided to use the radiator thicknesses listed in Table VII, to maximize the kilovoltage of the primary beam, to make the

TABLE VII

CHARACTERISTICS OF THE FLUORESCENT SOURCES

Atomic Number	Radiator Material	Radiator* Thickness (g/cm^2)	$K\alpha_1$ (kev)	$K\alpha_2$ (kev)	$K\beta_1$ (kev)	$K\beta_2$ (kev)	Weighted** Average Energy (kev)	Aluminum L-line Filters g/cm^2	Scattered Radiation in Fluorescent Source (per cent)	Exposure *** Rate at 50 cm (mr/min)
47	Silver	0.074	22.162	21.988	24.942	25.454	22.59	0.103	2	60
56	Barium	0.13	32.191	31.815	36.376	37.255	32.81	0.103	4	55
64	Gd_2O_3	0.23	42.983	42.280	48.718	49.961	43.78	0.103	4	43
66	Dy_2O_3	0.26	45.985	45.193	52.178	53.491	46.83	0.215	4	38
68	Er_2O_3	0.30	49.099	48.205	55.690	57.088	49.99	0.215	5	35
70	Yb_2O_3	0.35	52.360	51.326	59.352	60.959	53.28	0.441	7	24
72	HfO_2	0.40	55.757	54.579	63.209	64.936	56.72	0.441	7	22
77	Iridium	0.55	64.886	63.278	73.549	75.605	65.94	0.441	12	19
82	Lead	0.72	74.957	72.794	84.922	87.343	76.08	0.441	13	18
92	Uranium	1.50	98.428	94.648	111.289	114.549	99.61	1.446	~15	12

*For the oxides only the mass of the rare earth is included.
**Assuming relative intensities of 1.0, 0.5, 0.25, and 0.05 for $K\alpha_1$, $K\alpha_2$, $K\beta_1$, and $K\beta_2$, respectively.[14]
***Primary x-ray source at 300 KV C.P. and 10 ma.

angle between the radiator and the primary beam 45 degrees, and to locate detectors at an angle of 90 degrees from the primary beam.

The experimental arrangement for producing fluorescent radiation is illustrated in Fig. 16. A 300 KV constant potential Norelco x-ray unit was used as the primary source. Except for the window, the x-ray tube was encased in a 1 in. thick lead housing to prevent radiation leakage. A 1.5 in. thick lead diaphragm having a tapered conical hole was placed in the window of the x-ray tube to reduce the size of the x-ray beam. A lead-lined brass cylinder was placed against the diaphragm and served as the radiator holder. The center of the radiator was 15 cm from the x-ray target and at an angle of 45 degrees to the central ray of the primary x rays. An 0.75 in. diameter hole in the radiator holder provided an exit for the fluorescent radiation. The size of the fluorescent beam was limited by two diaphragms. Exposure-measuring instruments and films were located between tracks on an instrument table at an angle of 90 degrees to the central ray of the primary beam. The primary beam was absorbed by a large lead-lined brass cylinder attached to the radiator holder.

The measurements of the purity and other characteristics of the fluorescent sources will be given after a description of the other types of sources used to measure the film response.

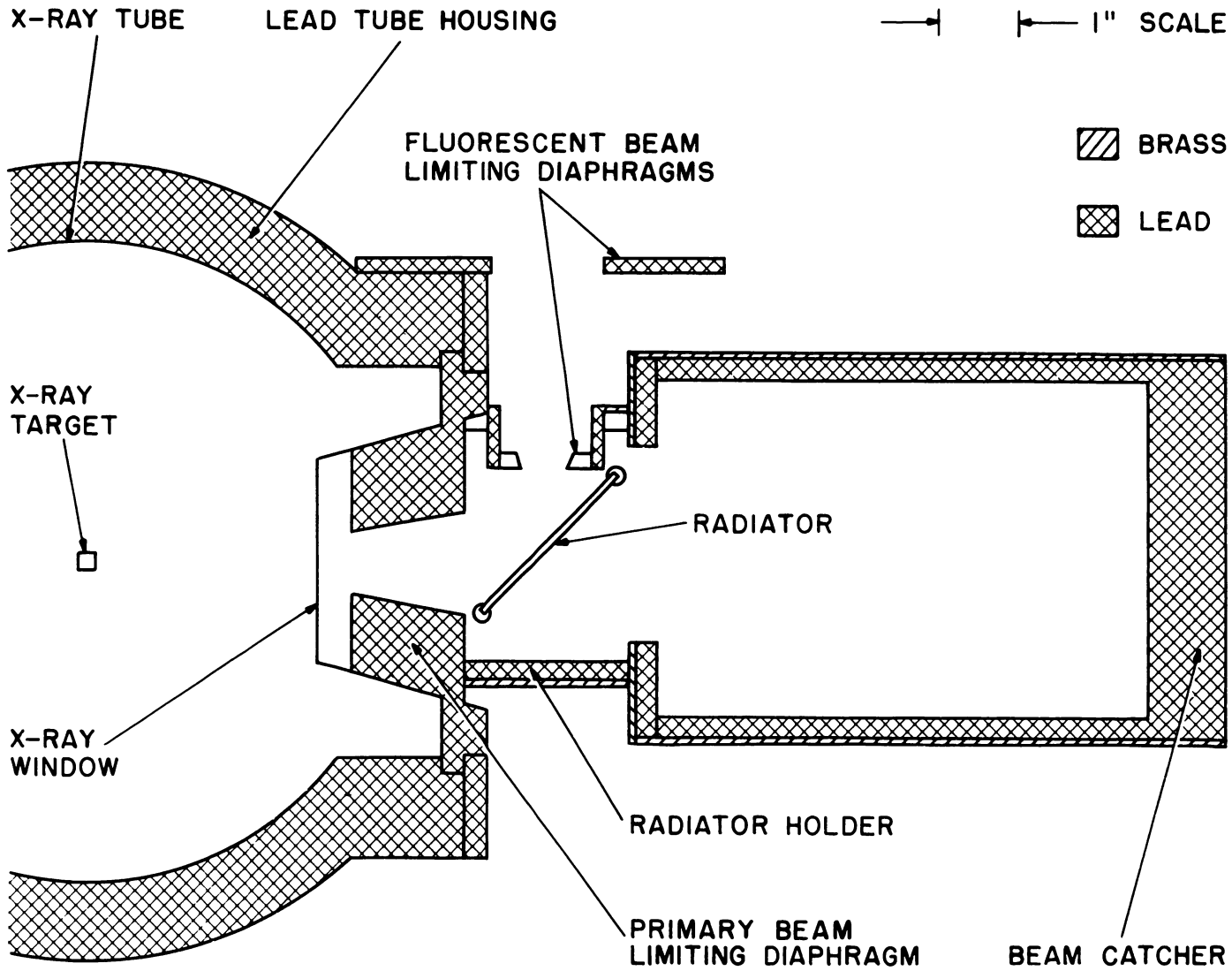

Fig. 16. Schematic diagram of the arrangement employed to obtain fluorescent radiation.

Heavily Filtered Direct X-Ray Sources

Since neither fluorescent radiation nor single line gamma-ray isotopes are available between 100 to 250 kev, it was necessary to use the direct x-ray beam with large amounts of filtration in order to cover this energy region.[3]

The effect of various thicknesses of absorbers on a continuous-spectrum x-ray beam is illustrated in Fig. 17, where the intensity in arbitrary units is plotted versus the x-ray energy for several thicknesses of copper filtration. The unfiltered spectrum is quite broad and contains large amounts of soft radiation. When a copper absorber is placed between the source and detector, the soft radiation is preferentially absorbed. As the copper thickness is increased, the energy at which the intensity is a maximum increases and the spectrum becomes narrower. Thus by using large amounts of filtration, a narrow spectrum band is obtained which sufficiently approaches monochromicity to be used to measure the response of a film. The amount of filtration, or the degree of monochromicity that can be achieved, is limited by the practical necessity of obtaining intensities which are large enough to calibrate film in a reasonable length of time.

The experimental arrangement employed to obtain the heavily filtered direct x-ray sources is illustrated in Fig. 18. The same 300 KV constant potential Norelco x-ray unit employed with the fluorescent sources was

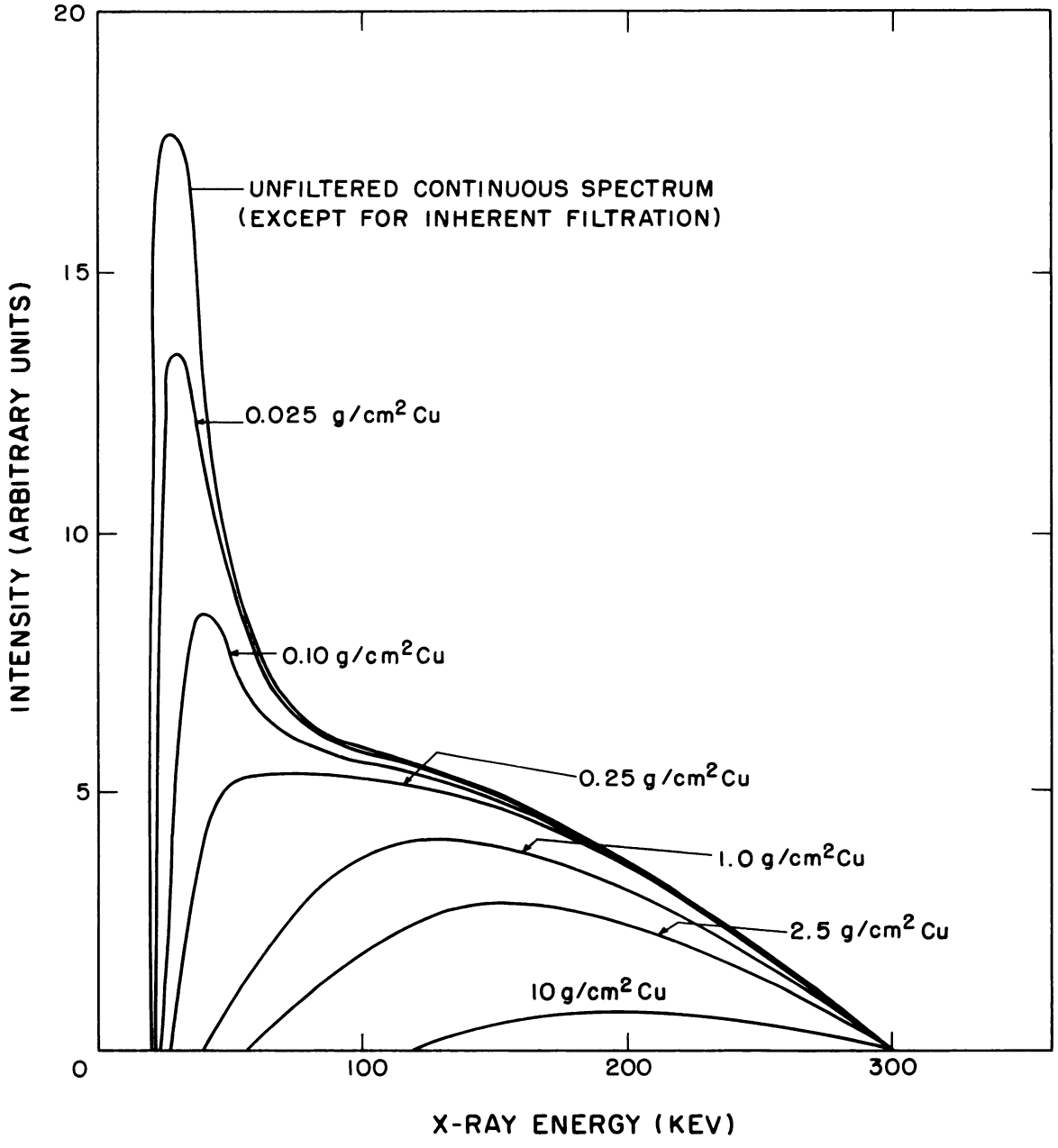

Fig. 17. The effect of various thicknesses of copper absorbers on a continuous-spectrum x-ray beam - 300 KV constant potential.

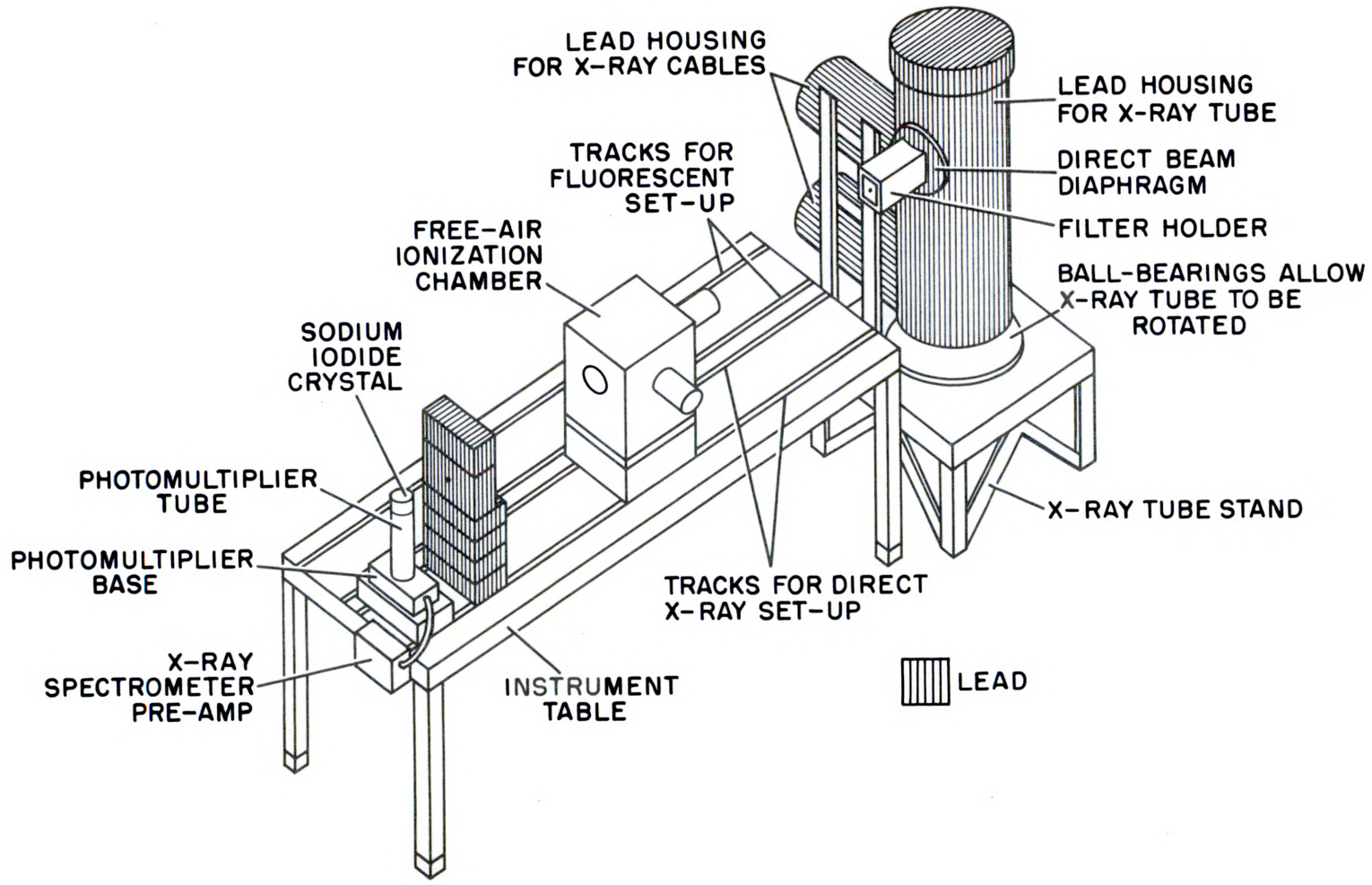

Fig. 18. Schematic diagram of the arrangement employed to obtain the heavily filtered direct x-ray sources.

used for the heavily filtered sources. A 1.5 in. thick lead diaphragm having a tapered conical hole was placed in the window of the x-ray tube to reduce the size of the beam. A rectangular steel box was mounted to the diaphragm to hold the thick filters. Instruments and films were located between tracks fastened to a table placed directly in front of the x-ray window. The central ray of the beam was directed midway between the tracks.

Table VIII gives the kilovoltages, the currents, and the thick filters employed with the direct x-ray beam to obtain effective energies of 84, 108, 135, 162, 205, and 242 kev. The method of determining the effective energy will be explained after the discussion of the radioisotope sources.

Radioisotope Sources

Gamma rays from radioisotopes were employed to cover the energy range above 250 kev. Since the film response changes very slowly in this region only three sources were used; they were Au^{198}, Cs^{137}, and Co^{60}.

The gamma-ray and x-ray energies emitted by these sources and their relative intensities are listed in Table IX. Of the four lines in Au^{198}, the 411 kev gamma ray is the most intense, but the 73 kev thallium x ray must be absorbed because the film is quite sensitive to low energy

TABLE VIII

CHARACTERISTICS OF THE HEAVILY FILTERED X-RAY SOURCES

Exciting Potential (kv)	X-Ray Current (ma)	Primary* Filter (g/cm^2)	Effective Energy (kev)	Spectral Peak (kev)	Spectral Width at Half-Height (kev)	Exposure Rate at 50 cm (mr/min)
100	15	2.0 Mo	84	86	24	70
130	15	4.0 Mo	108	108	30	67
170	15	8.0 Mo	135	140	36	95
200	15	9.0 Sn	162	164	39	72
250	10	15.0 Sn	205	205	46	73
300	10	8.0 Pb	242	247	60	68

*Filters placed between two 1/32 in. thick aluminum sheets.

TABLE IX

CHARACTERISTICS OF THE RADIOISOTOPE SOURCES

Isotopes	Gamma Rays* (kev)	X Rays* (kev)	Lead Filter Thickness (g/cm^2)	Exposure Rate at 40 cm (mr/min)
Au^{198}	411 (1), 680 (0.01), 1090 (0.025)	73 (0.02)	4.0	100
Cs^{137}	661 (1)	32 (0.1)	4.0	260
Co^{60}	1170 (1), 1330 (1)		0	170

*Relative intensity in parentheses.

radiation. Similarly, when the 32 kev barium x ray is absorbed, the Cs^{137} becomes a monochromatic 661 kev source. The two gamma rays in Co^{60} are of equal intensity and close in energy; for film response measurements the two lines may be averaged and Co^{60} considered a 1250 kev source.

The experimental arrangement employed with the radioisotopes is illustrated in Fig. 19. The sources were enclosed in either an aluminum or steel capsule of sufficient thickness to absorb the beta radiation emitted by the source. The source and capsule were then placed in a polystyrene source holder of sufficient thickness to absorb electrons produced by the gamma rays absorbed in the capsule. The source holder was located in a polystyrene rod at a height of 40 cm above the table. Exposure-measuring instruments and films were located 40 cm above the table and 40 cm from the source. To minimize scatter and achieve a narrow beam geometry for filtration measurements, lead diaphragms were placed in front of both the source and detector. However, the film response measurements were made both with and without the lead diaphragms in position.

SOURCE CHARACTERISTICS

The measurements to determine such characteristics of the sources as beam uniformity, spectrum purity, and exposure rates will now be presented.

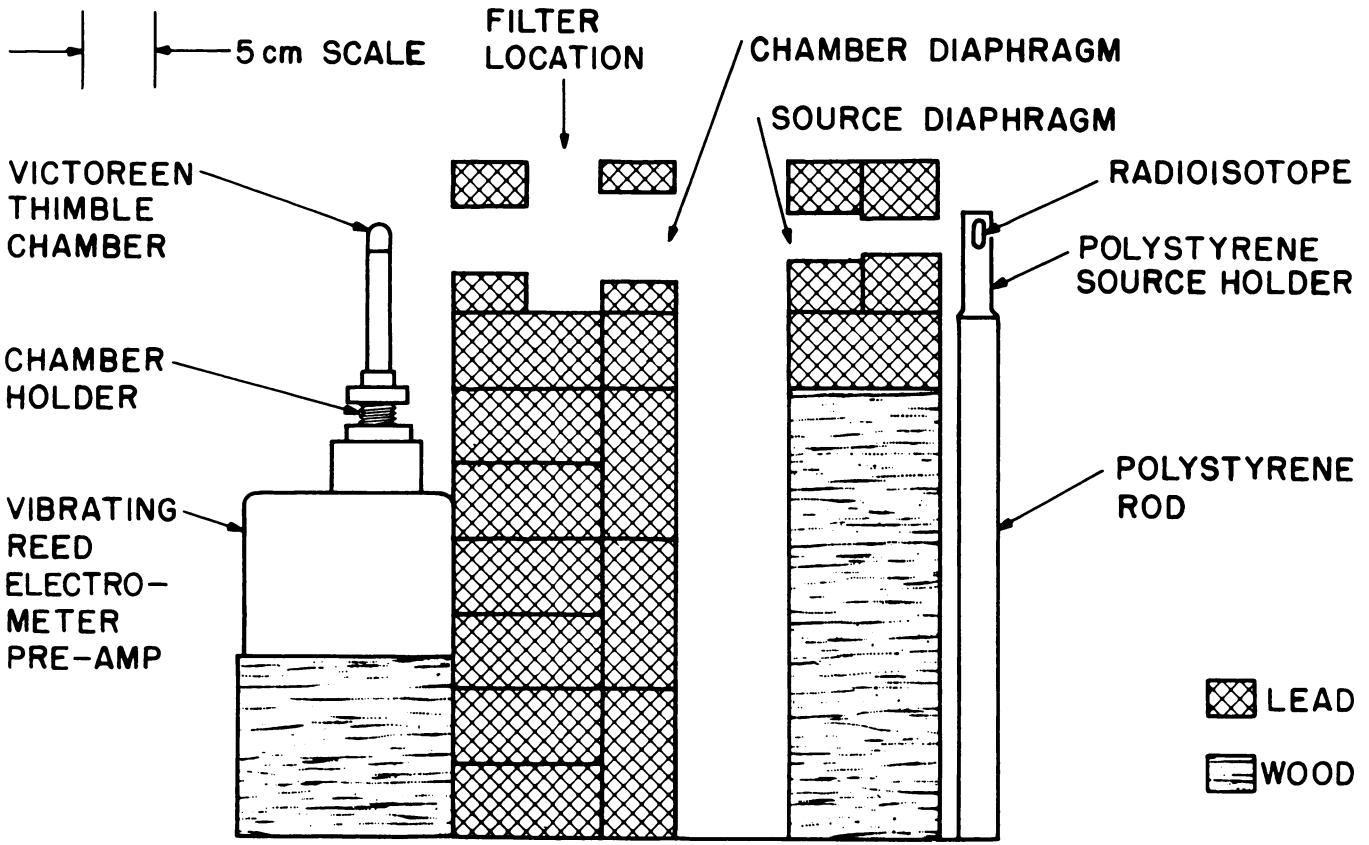

Fig. 19. Schematic diagram of the arrangement employed to obtain filtration measurements with the radioisotopes.

Beam Uniformity

To determine whether the detectors would be uniformly irradiated, intensity measurements with a photographic film were made at the detector locations. A free-air ionization chamber, the standard instrument for measuring the exposure of x-ray energies below 250 kev, and a Victoreen thimble chamber, the standard instrument for measuring the exposure of x-ray energies above 250 kev, were used as detectors in addition to the personnel monitoring film whose response was to be measured. The diameter of the entrance diaphragm of the free-air ionization chamber is 1.0 cm. The cylindrical measuring volume of the 25 r Victoreen thimble chamber is 2 cm in diameter and 2.5 cm in length. The rectangular monitoring film is about 3 x 4 cm in size, but the area read in the densitometer is 0.6 x 0.6 cm. Thus the intensity of the source had to be uniform over a circular area about 3 cm in diameter to irradiate all the detectors uniformly.

A similar procedure for measuring the beam uniformity was followed with all three types of sources. With the fluorescent and heavily filtered sources a film holder containing a 5 x 7 in. Eastman Type AA film was centrally located between the tracks of the instrument table and at the same height as the center of the source diaphragm; thus, the center of the film coincided with the center of the detectors. With the radioisotopes the film holder was located at the center of the detector position and measurements were taken with and without the lead

diaphragms. The 5 x 7 in. films were exposed, developed, read along several diameters, and the densities converted to roentgens using appropriate calibration curves.

Typical results are shown for all three types of sources in Fig. 20, where the variation in exposure along the vertical and horizontal diameters is plotted versus the position on the film where the readings were taken. The zero position on the abscissa corresponds to the center of the 5 x 7 in. film and the center of the detectors. Distances to the right and left of center on the horizontal diameter and distances above and below center on the vertical diameter are given in centimeters. The figure shows that a region of uniform intensity is obtained with all three types of sources, and measurements of several other diameters across the 5 x 7 in. film established that the uniform region is approximately circular. The beam is considered to be uniform enough where the exposure on the film does not vary by more than 2 per cent.

The diameter of the uniform region was 4, 8, and 12 cm at distances from the fluorescent sources of 25, 50, and 100 cm, respectively. The diameter of the uniform region was 3, 4, and 8 cm at distances from the heavily filtered sources of 35, 50, and 100 cm, respectively. The diameter of the uniform region 40 cm from the radioisotope sources was 3 cm with the lead diaphragms and 12 cm without the diaphragms. Thus the beams of all three types of sources were sufficiently wide to irradiate the detectors uniformly.

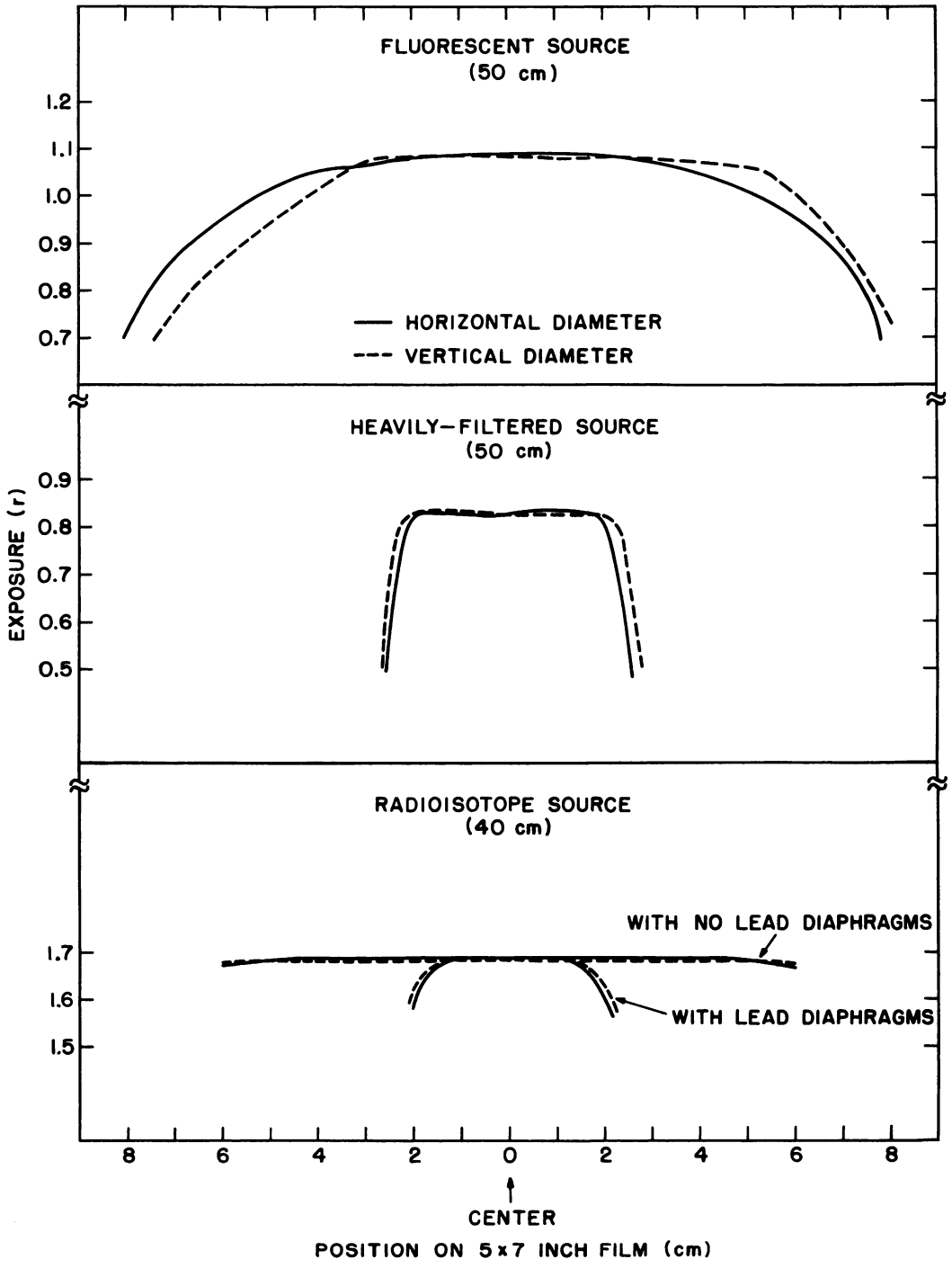

Fig. 20. Beam uniformity measurements of a fluorescent, a heavily filtered, and a radioisotope source.

Spectrum Purity

The spectrum purity of each source was determined primarily by absorption measurements. The analysis is based on the fact that with a monochromatic or narrow energy band x-ray source a linear absorption curve is obtained whose slope gives the absorption coefficient and thus the energy of the source, whereas with a continuous spectrum x-ray source a non-linear absorption curve is obtained. Hence the degree to which the absorption curve is linear and the degree to which the slope agrees with the theoretical value of $\mu^{6,9}$ determines the spectrum purity of the source.

The absorption measurements with the fluorescent and heavily filtered sources were made with a free-air ionization chamber. The ion current was measured with an Applied Physics Corporation Model 30D vibrating reed electrometer, and the absorbers were placed over the source diaphragm. Aluminum filters were used to absorb the L-lines of the fluorescent sources. The absorber thickness required to remove the L-lines was determined by absorption measurements; the L-line absorber thickness for each fluorescent source is given in Table VII. The absorption measurements with the radioisotope sources were made with a Victoreen 25-r Model 553 high-energy thimble chamber. In Fig. 19 the thimble chamber is shown in the pre-amp head of the vibrating reed electrometer which was again used to measure the ion current. The absorbers were placed over the chamber diaphragm.

The absorption curves obtained with the fluorescent sources are shown in Fig. 21, where the logarithm of the x-ray transmission through the aluminum absorbers is plotted versus the aluminum absorber thickness. The L-line absorber is not included in these thicknesses; that is, by zero filtration is meant no filtration except for the L-line filter. The absorption curves are quite similar. The first portion of the curve is linear and the slope is in agreement with the theoretical absorption coefficient of a monochromatic x-ray source having the weighted average energy of the K-lines. With thick absorbers the scattered primary x ray becomes significant because it has a higher effective energy than the K-lines, which are absorbed to a greater extent, making the curve non-linear.

The uranium is the only source that gives a linear absorption curve throughout the entire measured range of absorber thicknesses. Since there is no apparent reason why the uranium source should have no scattered radiation, it is reasonable to assume that the uranium curve remains linear because the effective energy of the scattered radiation is about the same as the weighted average energy of the K-lines, or about 100 kev. The average energy of the 300 KV, unfiltered continuous spectrum x-ray source is about 150 kev, and when a 150 kev x ray is scattered through a 90 degree angle it loses about 35 kev. Thus, an effective energy of about 100 kev for the scattered radiation is not unreasonable.

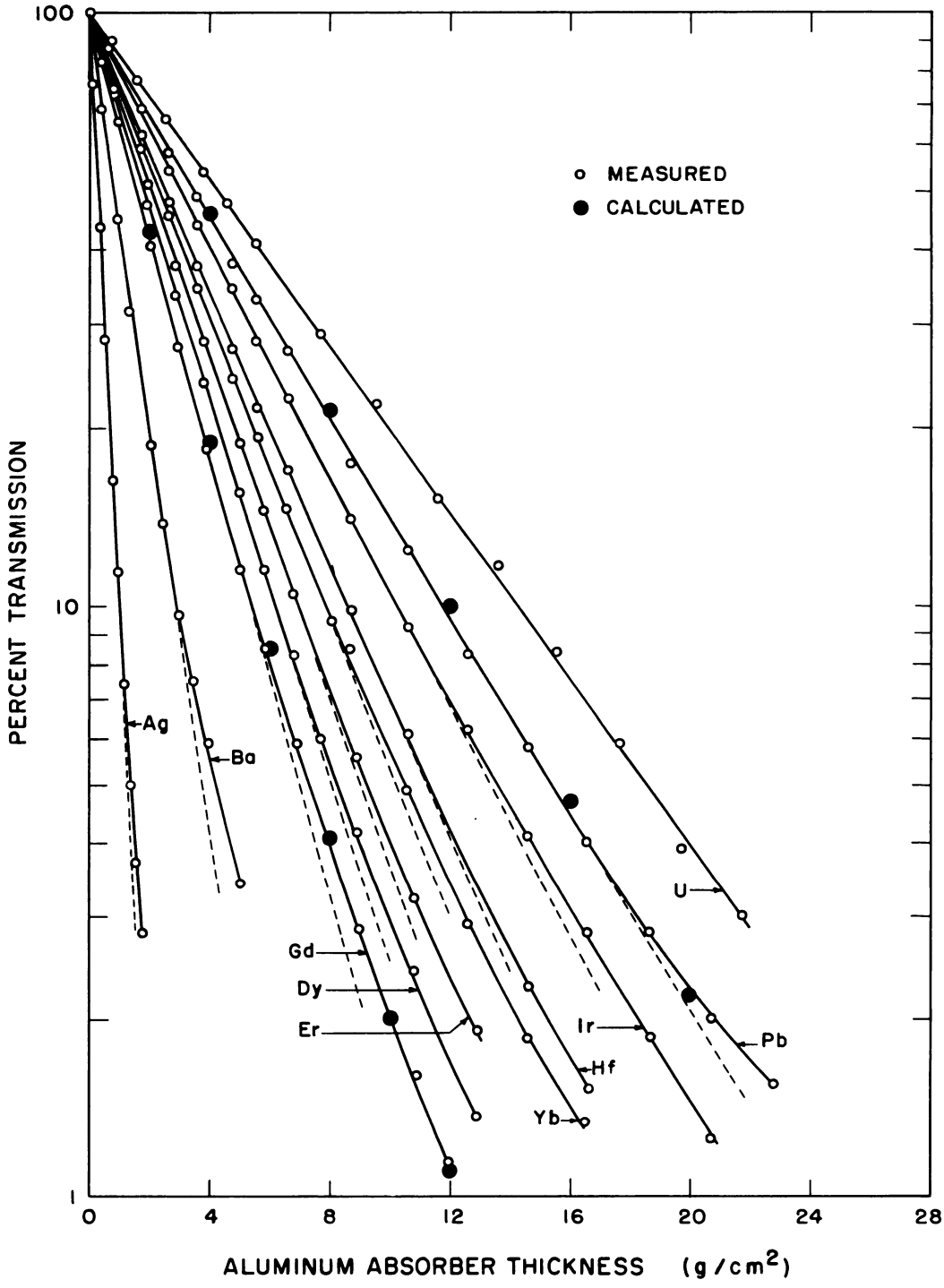

Fig. 21. Aluminum absorption curves obtained with the fluorescent sources.

The percentage of scattered radiation in the fluorescent sources was estimated assuming the effective energy of the scattered radiation was 100 kev and using the equation

$$I = I_F e^{-\mu_F x} + I_S e^{-\mu_S x} \quad ,$$

where I is the measured intensity at absorber thickness x, I_F is the fraction of the measured intensity due to fluorescent radiation, I_S is the fraction of the measured intensity due to scattered radiation, μ_F is the aluminum absorption coefficient of the fluorescent radiation, and μ_S is the aluminum absorption coefficient of the scattered radiation. For a large x, several values of I_F and I_S were tried until the measured value of I was obtained. The values of I_F and I_S which gave the measured I at the large x were then used to compute I for several other values of x, and the results are shown in Fig. 21 for the gadolinium and lead sources. The calculated absorption curves obtained by this method were in close agreement with the measured absorption curves for all the fluorescent sources.

The percentage of scattered radiation in the fluorescent sources derived by this method is given in Table VII. Since the aluminum absorption coefficients change slowly between 80 and 120 kev, the estimated percentage of the scattered radiation would not change significantly if these energies instead of 100 kev were assumed for the effective energy of the scattered radiation.

Table VII shows that the scatter tends to increase as the atomic number of the fluorescent source increases. By plotting the percentage of scattered radiation versus atomic number, the scattered radiation from the uranium source was estimated to be about 15 per cent.

The absorption curves obtained with the heavily filtered sources are shown in Fig. 22, where the x-ray transmission is plotted versus the thickness of the molybdenum absorbers. The heavy filter is not included in these thicknesses; that is, by zero filtration is meant no filtration except that of the heavy primary filter. Over the range of thicknesses employed, the absorption curves are linear. From the slope, the absorption coefficient and thus the effective energy of each source was determined. The effective energies are listed in Table VIII, and they have been used to label the absorption curves in Fig. 22.

X-ray spectrometer measurements were made to determine the energy spread of the heavily filtered sources. The sodium-iodide crystal, the photomultiplier tube, the tube base, and the pre-amp of the x-ray spectrometer were placed on the instrument table and shielded by a 2 in. thick lead brick wall as shown in Fig. 18. A 0.04 in. hole in the lead shield permitted the x-ray beam to strike the center of the crystal which was located 150 cm from the x-ray target. For the spectrometer measurements, the diameter of the source diaphragm was reduced from 5/8 to 1/4 in. The smaller source diaphragm and the 0.040 in. diameter

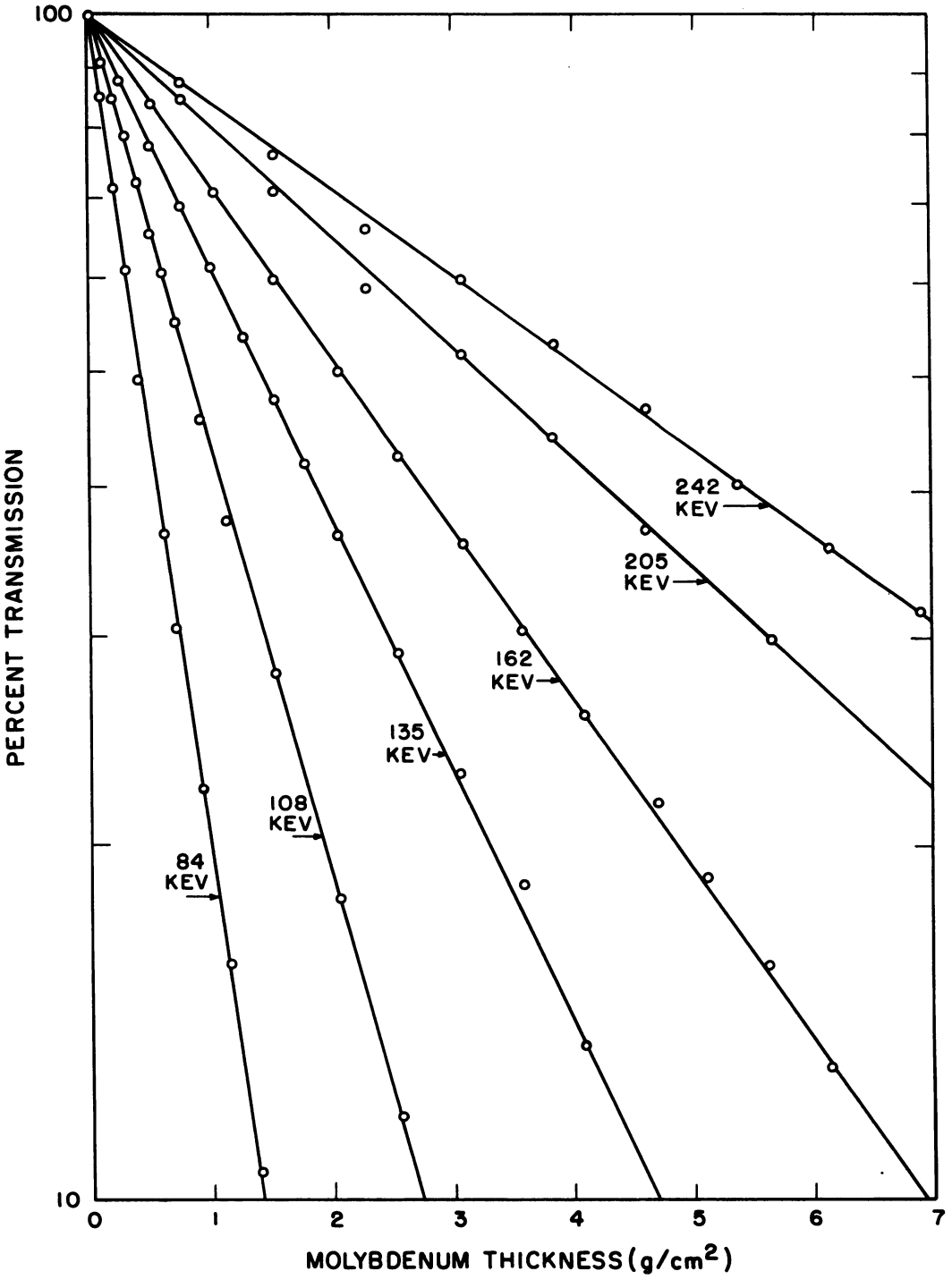

Fig. 22. Molybdenum absorption curves obtained with the heavily filtered direct x-ray sources.

crystal diaphragm were necessary in order to reduce the x-ray intensity to a level low enough to be counted. To be certain that only the radiation entering the crystal was counted, background measurements were made with the x-ray unit on and the 0.040 in. hole plugged, and this background count was subtracted from the total counting rate. The spectrometer was calibrated with the Lu^{177} lines at 56, 112, and 208 kev and the Hg^{203} lines at 73 and 279 kev.

The x-ray spectrometer measurements of the heavily filtered sources are shown in Fig. 23, where the number of counts/cm^2-sec-kev is plotted versus the x-ray energy. The curves are labeled with the effective energies derived from the absorption measurements. The energy at which the intensity is a maximum, or the peak energy, is in every case within 5 kev of the effective energy. The energy spread of a heavily filtered beam is usually expressed in terms of the spectral width at half-height. The spectral width at half-height is given in Table VIII for each source, together with the peak energy. In each case the spectral width at half-height is within 22 to 28 per cent of the peak energy.

The absorption curves obtained with the radioisotope sources are shown in Fig. 24, where the gamma-ray transmission is plotted versus the lead absorber thicknesses. Both the Au^{198} and the Cs^{137} curves show the presence of the low energy photons emitted by these sources

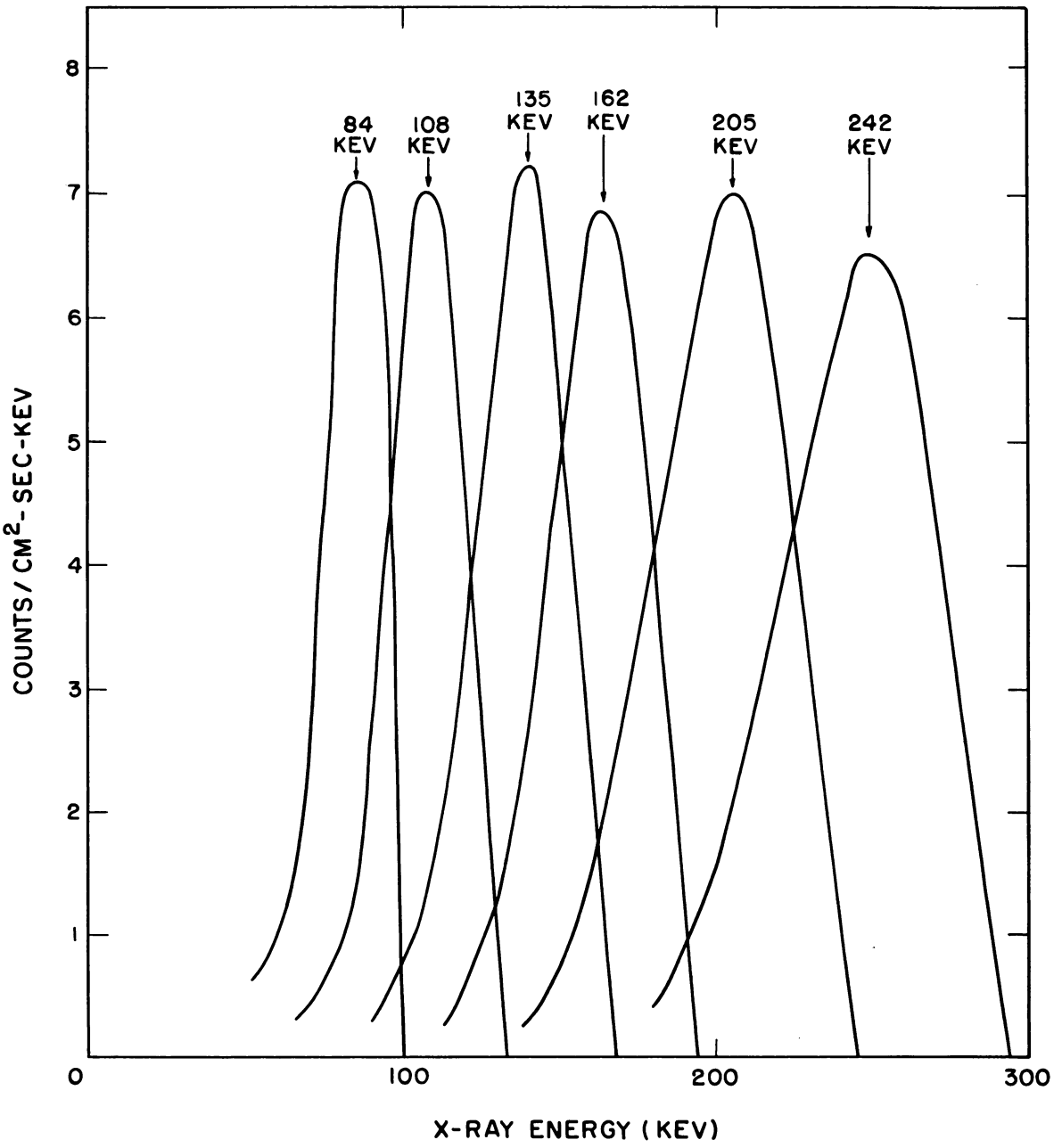

Fig. 23. X-ray spectrometer measurements of the heavily filtered direct x-ray sources.

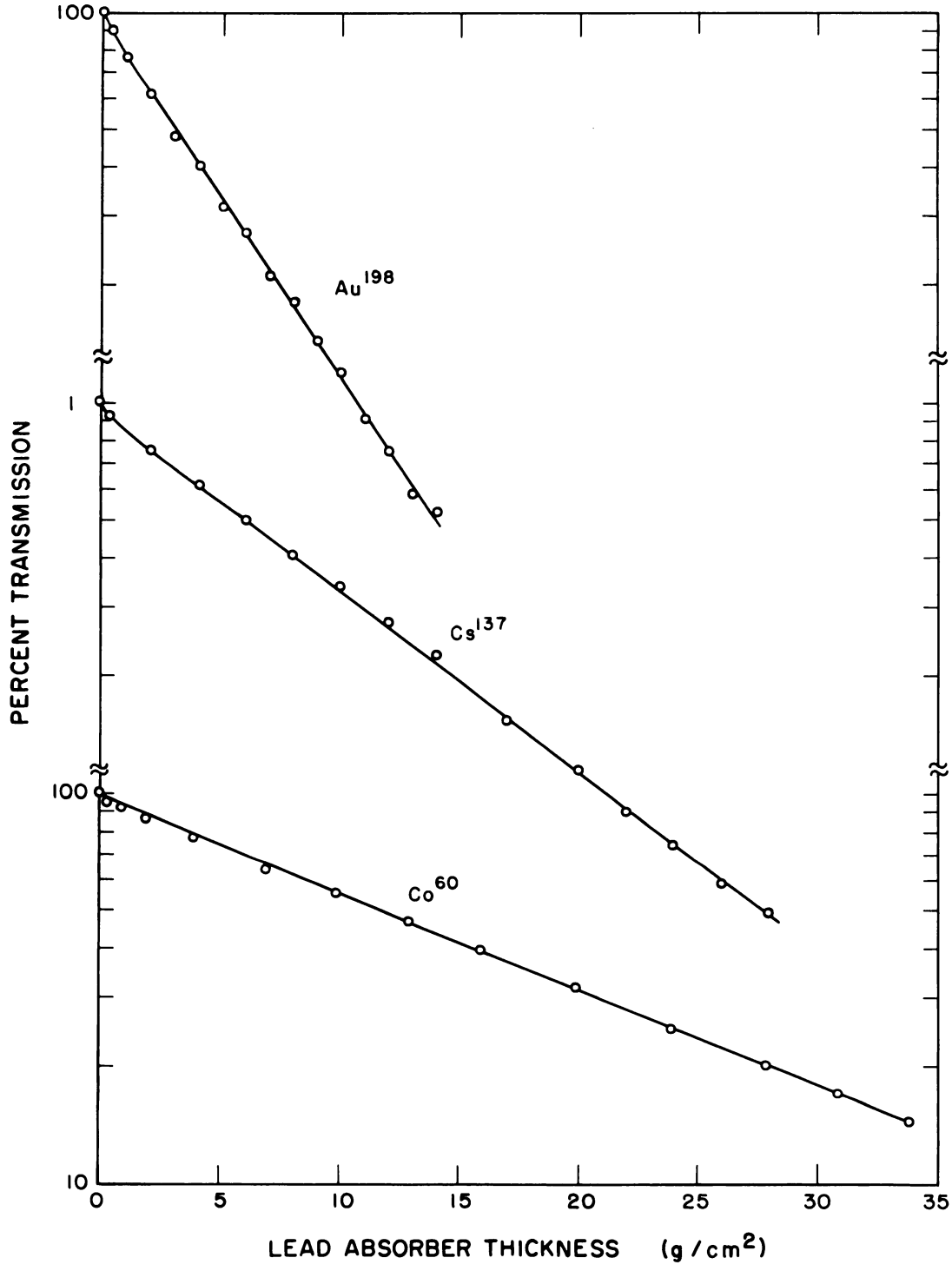

Fig. 24. Lead absorption curves obtained with the radioisotope sources.

which are listed in Table IX. The absorption curves decrease relatively rapidly at first, but when the absorber thickness becomes large enough to absorb the softer photons the curves decrease less rapidly and become linear. The slope of the linear portion of the Au^{198} curve is in agreement with the theoretical value of a 411 kev source, and the slope of the linear portion of the Cs^{137} curve is in agreement with the theoretical value of a 661 kev source. The film response measurements were made with the Au^{198} and Cs^{137} sources filtered by 4 g/cm^2 of lead, enough to eliminate the softer components. The slope of the linear absorption curve obtained with the Co^{60} source is in agreement with the theoretical value expected from a 1250 kev source.

Exposure Rates

The exposure rates of the fluorescent and heavily filtered sources were measured with a free-air ionization chamber. A Victoreen thimble chamber was used to measure the exposure rates of the radioisotope sources.

The design of the free-air ionization chamber was similar to that employed by the National Bureau of Standards.[15] The chamber consists of an electrode system mounted symmetrically in a case having a beam-limiting diaphragm entrance and an exit hole for the x rays. The electrode system consists of two parallel plate electrodes separated by insulated rods located at each corner of the plates and an end-guard assembly

which is attached to the rods. The x rays pass between the two parallel plate electrodes, one of which is at ground potential and the other at high potential, and the ions produced in the collecting region are measured.

A diagrammatic sketch of the free-air chamber is shown in Fig. 25. The aquadag-coated polystyrene electrodes are 18 cm long and 29 cm wide. One of the electrodes is at a potential of 1500 volts, enough to assure voltage saturation at the highest x-ray intensity employed. The other electrode consists of a guard plate at ground potential in the center of which is a collecting area 5 cm long and 16 cm wide. The electrode separation is 16 cm; from the data of Attix and DeLa Vergne[16] it was estimated that the ionization losses in the 16 cm separation would be less than 1 per cent at 40 kev and about 3 per cent at 242 kev.

The purpose of the end-guard assembly is to make the electric field between the collecting and high potential electrodes uniform. It consists of sixteen 0.7 cm wide strips of aluminum which are attached to the insulating rods with a separation of 0.3 cm. The aluminum strips are at right angles to the electrodes. The guard assembly was constructed from a sheet of aluminized mylar from which 0.3 cm wide aluminum strips were removed. Seventeen 1-megohm resistors were connected in series to the electrodes and aluminum strips to divide the potential uniformly. To determine whether the electric field

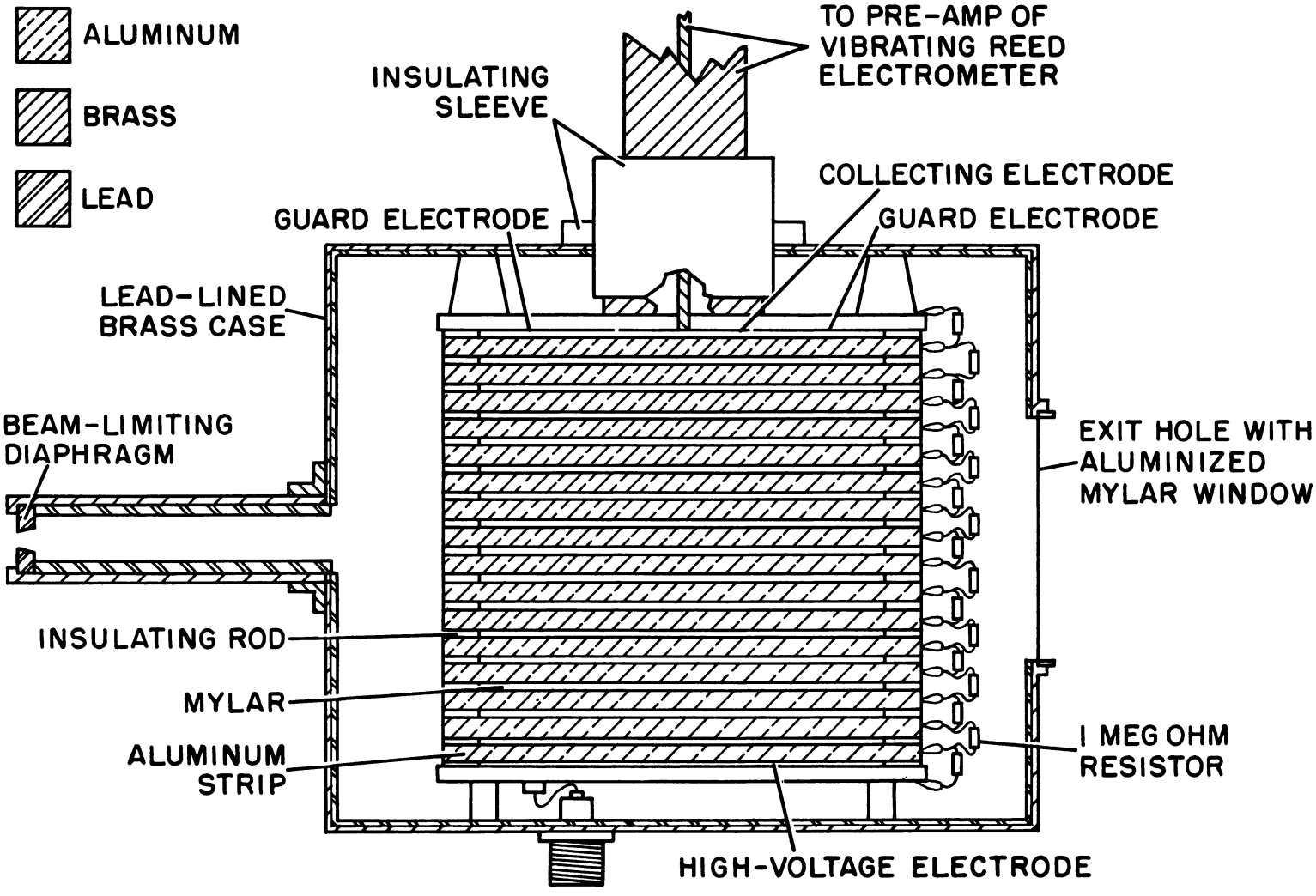

Fig. 25. Diagrammatic sketch of the free-air ionization chamber.

was uniform, ionization measurements were made with the lead-lined brass case surrounding the electrode system first at ground potential and secondly at high potential. If the electric field were distorted inward giving a lower ion current with the case at ground potential, it would be distorted outward with the case at high potential, giving a higher ion current. The ionization measurements made with the case at ground and high potential agreed within 0.3 per cent, indicating that the field was adequately uniform.

The chamber was placed between the tracks of the instrument table as shown in Fig. 18 with the beam-limiting chamber diaphragm aligned with the source diaphragm. The ion current was measured using the vibrating reed electrometer as a null detector. The current passed through a calibrated 10^{11} ohm resistor, and the resulting voltage drop was compensated by a Rubicon potentiometer connected in series.

The exposure rate in r/sec was calculated from the measured current I, in esu, using the equation

$$\text{r/sec} = \frac{I}{V} \times \frac{76}{P} \times \frac{T + 273}{273}$$

where V is the collecting volume in cm^3, P is the pressure in cm, and T is the temperature in °C. The collecting volume is given[17] by $\pi b^2 L$, where b is the radius of the beam-limiting diaphragm (0.5 cm), and L is the length of the collecting electrode (5.0 cm).

The exposure rates were measured at several distances along the instrument track. The heavily filtered sources obeyed the inverse square law with distances measured from the x-ray target to the beam-limiting diaphragm of the chamber, whereas the fluorescent sources obeyed the inverse square law with distances measured from the source diaphragm to the beam-limiting chamber diaphragm. These results are in accord with the geometrical analysis made by Taylor[17] of how measurements with the free-air chamber diaphragm system would obey the inverse square law with a point source (the x-ray target) and an extended source (the fluorescent radiators).

A Victoreen 25-r Model 553 thimble chamber was used to measure the exposure rates of the radioisotope sources. It consists of an ionization chamber with an air volume of 1.83 cm^3 mounted at one end of a shielded stem containing a polystyrene condenser connected in parallel with the chamber. The chamber is charged, and its potential after irradiation is read with a Victoreen Model 70 electrometer. The nylon wall of the ionization chamber is 0.45 g/cm^2 thick. The intensity limit of the chamber when used with the Model 70 electrometer is 900 r/min at full scale which is well beyond the rates measured with the radioisotopes. The thimble chamber was calibrated by the National Bureau of Standards with a known Co^{60} source. The exposure rates measured 40 cm from the radioisotope sources are given in Table IX.

REFERENCES

1. Storm, E., and Bemis, E., "A Method for Monitoring X-rays Using Eastman Type K Film", Los Alamos Scientific Laboratory report LA-1107, 1950.

2. Hoerlin, H., Clark, R. H., Jones, D. P., Kazuba, F. J., and Larson, E. F., "Development of a Wavelength-Independent Radiation Monitoring Film", Argonne National Laboratory report ANL-5168, 1953.

3. Ehrlich, M., and Fitch, S. H., "Photographic X- and Gamma-Ray Dosimetry", Nucleonics 9, 3, 5-17 (1951).

4. Ehrlich, M., "A Photographic Personnel Dosimeter for X-radiation in the Range from 30 Kev to Beyond 1 Mev", Radiology 68, 549-54 (1957).

5. Storm, E., Gilbert, H. E., Israel, H., "Gamma Ray Absorption Coefficients for Elements 1 through 100 Derived from the Theoretical Values of the National Bureau of Standards", Los Alamos Scientific Laboratory report LA-2237, 1957.

6. Grodstein, G. W., "X-ray Attenuation Coefficients from 10 Kev to 100 Mev", NBS Circular 583, 1957.

7. Ehrlich, M , personal communication.

8. Storm, E., "The Response of Film to X-Radiation of Energy Up to 10 Mev", Los Alamos Scientific Laboratory report LA-1220, 1951.

9. McGinnies, R. T., "X-ray Attenuation Coefficients from 10 Kev to 100 Mev", Supplement to NBS Circular 583, 1959.

10. Ehrlich, M., "The Sensitivity of Photographic Film to 3 Mev Neutrons and to Thermal Neutrons", Health Phys. 4 (1960).

11. "Protection Against Neutron Radiation up to 30 Million Electron Volts", NBS Handbook 63, p. 66, 1957.

12. Ballinger, E. R., personal communication.

13. Sayeg, J. A., personal communication.

14. Compton, A. H., and Allison, S. K., "X-rays in Theory and Experiment" (D. Van Nostrand Company, New York, 1935) p.640.

15. Taylor, L. S., and Singer, S., "An Improved Form of Standard Ionization Chamber", Radiology 15, 637-46 (1930).

16. Attix, F. H., and DeLa Vergne, L., "Plate-Separation Requirements for Standard Free-Air Ionization Chambers", J. Res. Natl. Bur. Std. A, 53, 393-402 (1954).

17. Taylor, L. S., "Analysis of Diaphragm System for the X-ray Standard Ionization Chamber", Radiology 15, 49-65 (1930).